CALIFORNIA ENERGY COMMISSION

Energy Efficient, Low Emission, Cost Effective MicroPilot® Ignited Natural Gas Engine Driven Genset For Deregulated, Distributed Power Generation Markets

CONSULTANT REPORT

March 2002
500-02-015F

CALIFORNIA ENERGY COMMISSION

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial / Agricultural / Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research.

What follows is the final report for the Energy Efficient, Low Emission, Cost Effective MicroPilot® Ignited Natural Gas Engine Driven Genset For Deregulated, Distributed Power Generation Markets, contract number 500-97-041 conducted by the Gas Research Institute and Clean Air Partners. The report is entitled Energy Efficient, Low Emission, Cost Effective MicroPilot® Ignited Natural Gas Engine Driven Genset For Deregulated, Distributed Power Generation Markets. This project contributes to the Environmentally-Preferred Advanced Generation program.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

Executive Summary

This project was proposed to and contracted by the Commission to GRI with a subcontract to BKM. Effective June 18, 2001, Clean Air Partners (CAP) has acquired BKM Business Development Corp (BKM). Clean Air Partners, through its license and business agreements with Caterpillar, develops and sells natural gas fueled Caterpillar engines worldwide. Additionally, CAP sells natural gas components, including injectors, worldwide. Since CAP's inception in 1992, BKM has provided all of the Company's engineering as well as component assembly, by contract.

Since the acquisition of BKM occurred during the term of this contract, and BKM no longer exists as a separate entity, we will generally refer to both entities as Clean Air Partners (CAP) in this report. In a few instances, we have referred to the organizations separately, for the purposes of clarity, for the time period prior to the acquisition.

Environmentally Preferred Advanced Generation is broadly defined as RD & D activities targeting the development of highly efficient generation technologies using clean fuels. This project was proposed to develop a lube oil MicroPilot®, compression ignition, natural gas fueled generator engine. Since the pilot and gas injection systems are less complex than either a diesel or spark gas system, the MicroPilot® approach offers the best efficiency (over 38%) and lowest installed cost per kW (under $200 $/kW) of any engine in the power class under 5mW. Spark ignition natural gas engines typically have an installed cost near $400/kW. This emissions-friendly engine technology will also significantly reduce the cost and the toxic environmental hazards associated with used engine oil disposal.

The goal of this project was to finish development and demonstrate a high efficiency, low initial cost, low operating cost, low emissions natural gas engine for use in a deregulated, distributed power generation market in California (and elsewhere). This project was a continuation of research and development previously funded by the Gas Research Institute (GRI).

This technology is known as MicroPilot® diesel cycle natural gas engines. This project, was proposed to complete the development of a 1% MicroPilot® engine and demonstrate a production-ready version of the MicroPilot® technology applied to the Caterpillar 3412 diesel generator set engine.

The MicroPilot® technology includes the following features:

- Lean burn combustion
- Unthrottled intake
- Timed port injection of gas
- Compression ignition of pilot diesel fuel
- Full time cycle-to-cycle electronic control of:
  - Air fuel ratio
  - Gas injection quantity and timing
  - MicroPilot® diesel quantity and timing

At part load conditions, the same specific emission levels have been achieved through full control of pilot and gas injection timings and the air / fuel ratio. CAP patented Skip-Fire (SF) technique and Turbo-Air-Bypass (TAB) device have proven to be very effective methods for controlling the air / fuel ratio and combustion characteristics at moderate and low load conditions. It is the SF and TAB that makes the two to three percent pilot fuel and high efficiency possible on an unthrottled, natural gas engine.

The stock diesel pencil-nozzle injectors were converted to electronically controlled pilot injectors delivering MicroPilot® fuel quantity (4-8 mm^3 / injection). It was demonstrated that the pilot injector spray jets have significant ignition energy and are capable of widely spreading over the combustion chamber. The small quantity injected is quite adequate to ignite air / gas mixtures up to an excess air ratio of two. Further reduced pilot delivery was not explored due to time and budget limitations; however, it was concluded that with special pilot injectors, scaled down in size, pilot quantities can be reduced to one percent at rated power.

Objectives

This project was intended to facilitate the earliest introduction of the MicroPilot® technology to field service. The goal was a genset package having diesel efficiency and with less than (<) 2g / hp-h NOx. Simultaneously, research was conducted to reduce the NOx level to < 1.5 g / hp-h maintaining or improving the thermal efficiency demonstrated with the 2 g NOx version. These improvements were expected from efforts of optimizing the combustion chamber and pilot injector spray characteristics using methodology developed by CAP.

Additionally, the utilization of lube-oil as pilot-fuel would be explored determining performance and emission characteristics. This practice would eliminate the need for oil changes thereby reducing maintenance costs. The successful use of lube-oil greatly depends on the quantity of pilot fuel, generally preferred to be less than 1 percent of the total fuel requirement.

The final goal is the technology transfer to the Caterpillar 3412 engine used more extensively for power generation.

The specific technical objectives upon which this project's success will be evaluated are:

- To test and develop a Caterpillar 3406 genset package with two percent MicroPilot® technology having 38 percent thermal efficiency or better with < 2g / hp-h NOx.
- To test and develop a Caterpillar 3406 genset package with one percent MicroPilot® technology having 38 percent thermal efficiency or better with < 1.5g / hp-h NOx using lube oil as the pilot fuel.
- To transfer both the two percent and the one percent MicroPilot® technology to a Caterpillar 3412 engine genset package, followed by troubleshooting unique 3412 problems. The goals for the Caterpillar 3412 with MicroPilot® are 38 percent thermal efficiency or better with < 2.0 g / hp-h NOx.

- To do durability testing on the Caterpillar 3412 engine genset using the MicroPilot® technology. The goals for this test are 38 percent thermal efficiency or better at < 2.0 g / hp-h NOx before and after the equivalent of 1000 hours of testing with 80 percent of the time at 60 percent load and 20 percent of the time at 100 percent load.

Approach

A four phase research and development programs was proposed, with Phase 1 funded in this program. The un-funded remaining phases focused on In-Cylinder Emissions Reduction (Phase II), Emissions Reduction Using after Treatment (Phase III) and Combustion System Optimization (Phase IV).

Phase I was funded by the Commission and focused on the development of a Caterpillar 3412 Genset with 1 percent MicroPilot® lube oil injection, demonstration project. This phase will start with the Caterpillar 3406 (6 cylinder) Genset Engine utilized in a previous project to demonstrate "proof of concept". This base engine will be used to develop the 1 percent pilot injection hardware and software, and lube oil injection system. Once this work is complete (Tasks 2.1 & 2.2), the hardware and software will be scaled and modified for the 12-cylinder version, the Caterpillar 3412 Genset Engine. The system will be performance and durability tested on the Caterpillar 3412 Genset in Tasks 2.3 & 2.4.

Benefits to California

- Additional options for low-cost environmentally preferred electric generation.
- Improved service through increased system reliability with the application of distributed power technologies.

Project Conclusions

1. The Caterpillar 3406 2 percent MicroPilot® genset engine survived the durability test while meeting the project objectives for pilot quantity, emissions and thermal efficiency.

- The genset was optimized to run at the following conditions:
  - NOx < 2.0 g / hp-h
  - Thermal Efficiency > 38 percent
  - Pilot Quantity 5.0 mm3 (2.25 percent) diesel per injection.
  - 80 hrs at 60 percent load (154 kW)
  - 20 hrs at 100 percent load (265 kW)
- Emissions and thermal efficiency goals were met through the following strategies:
  - Optimized gas lambda with TAB valve air / fuel ratio control.
  - Minimized pilot quantity through calibration and testing
  - Optimized pilot timing through testing and NOx / Thermal efficiency tradeoff.
- The genset achieved the goal of low initial cost per kilowatt by the following strategies:
  - No cylinder head modifications were required.
  - Stock diesel injector (with modifications) was used for pilot injection.
  - Continuous rating of 265 kW was achieved.

2. The operation of the Caterpillar 3406 on one percent MicroPilot® was evaluated. Physical limitations were encountered in modifying the stock diesel injectors for one percent MicroPilot® operation.
    - Adequate spray patterns for one percent MicroPilot® could not be achieved with modified stock diesel injectors.
    - Operation of the 3406 genset on 1.2 percent lube oil pilot has been demonstrated.
    - The 3406 1.2 percent Lube Oil MicroPilot® genset did not meet the project goal of 1.5 g/hp-hr NOx at 38 percent or greater thermal efficiency.
    - The one percent MicroPilot® system using the modified standard Caterpillar diesel injectors is not adequate for dual fuel pilot ignition.
3. The modification of the Caterpillar 3412 diesel engine to MicroPilot® operation posed significant unanticipated challenges.
    - Physical layout of the V-12 engine and complexities with the intake manifold relative to the MicroPilot® installation on the Caterpillar 3406 (6 cylinder) intake system.
    - The CAP engine control unit has output capacity limitations
    - The need for two gas valves per cylinder
    - Uneven firing order. It was determined that the 3412 engine is an uneven firing engine, whereas most 12-cylinder engines fire every 60°; the 3412 fires every 55° then 65°.
    - Natural gas injection system
    - Fuel pump plate
    - Electronic Pressure Regulator Block
    - Air handling system
    - After cooler system
4. Funding, market and time constraints resulted in the mutual agreement to terminate further development of the Caterpillar 3412 MicroPilot® system.
    - The diesel CAT 3412 Genset was to be discontinued.
    - The diesel fuel injectors for the CAT 3412, on which the CAT 3412 MicroPilot® is based, are being phased-out of production.
    - The CAP electronic control unit does not have the capacity to support the 3412 MicroPilot® product. Using two of the current ECU's is difficult to implement and not a production viable solution. A new ECU development project is outside the scope of this project and would significantly lengthen the products time to market.

Project Recommendations

1. Continue to develop application of the CAT 3406 MicroPilot® genset for field service.
    - Additional software upgrades are required before the MicroPilot® system can be placed in service for additional testing and durability. These upgrades include:

- Automatic starting and stopping routines.
- Complete integration of ECU with generator control panel.
- Speed governor upgrades are needed to accept sudden load changes on lube oil.

- Initial lube oil injection tests have shown that a smaller fuel pump driven with an electric motor is able to supply the same amount of rail pressure and fuel quantity for operation. This configuration should be investigated further due to the benefits of better starting, easier installation and lower cost.
- Design an optimized 1% MicroPilot® injector and retest lube oil and diesel NOx / thermal efficiency tradeoff.
- MicroPilot® operation with lube oil (in place of diesel fuel) would require additional development and systems.
  - Use of ashless lube oil is needed to be compatible with the MicroPilot® system. Ashless oil is not currently certified by the engine manufactures for engine durability. Therefore, to use lube oil as the MicroPilot® fuel, we need to certify (and possibly re-formulate) ashless lube oil for engine crankcase use.
  - Development of a lube oil pre-heat system for MicroPilot® injection during engine start. The lube oil needs to be heated to attain the proper spray characteristics for cold engine start. Once the engine is at operating temperature, the lube oil temperature is adequate to maintain the proper spray characteristics.

2. Discontinue development of the CAT 3412 MicroPilot® system because of funding, market and time constraints.
   - Further develop and durability test the CAT 3406 MicroPilot® system for commercial introduction
   - Initial product introduction would be with the 2 percent MicroPilot® using diesel fuel injection.
   - Additional development is needed before lube oil MicroPilot® is commercially viable.
   - Exhaust aftertreatment systems need to be developed and tested to reduce the exhaust emission to lower levels.
3. Identify additional appropriate diesel engine gensets for future application of the MicroPilot® system.

Abstract

Environmentally Preferred Advanced Generation is broadly defined as RD & D activities targeting the development of highly efficient generation technologies using clean fuels. In distributed power applications, low-cost, low-emission generators are required to benefit the needs of California electric consumers. This project was proposed to develop a lube oil MicroPilot®, compression ignition, natural gas fueled generator engine. Since the pilot and gas injection systems are less complex than either a diesel or spark gas system, the MicroPilot® approach offers the best efficiency (over 38 percent) and lowest installed cost per kW (under $200 / kW) of any engine in the power class under 5mW. Prior work had demonstrated the application of 2 percent MicroPilot® on a CAT 3406 engine in the laboratory. This project was to further the development of this system, apply it in a genset application, investigate reducing the injection quantity to 1 percent (diesel and / or lube oil), replacing the diesel with lube oil MicroPilot® injection, and application of the technology to the CAT 3412 genset engine. The 2 percent MicroPilot® system was successfully applied to the CAT 3406 genset engine and tested for 100 hours. Achieving 1 percent MicroPilot® operation at acceptable efficiency was not achievable with the current MicroPilot® injectors, although 1.2 percent MicroPilot® was demonstrated. The MicroPilot® injectors are based on modified production components, and adequate spray patterns at 1 percent injection rates could not be achieved. A redesign of the injectors should overcome this problem, but was not part of the program plan or budget. The substitution of lube oil for diesel as the MicroPilot® injection fuel was investigated. It was demonstrated that lube oil could be used in place of diesel for the MicroPilot® injection, but there were two issues to be resolved prior to commercial application; ashless lube oil would be required (and be accepted by the engine manufacturer) and the lube oil would need to be heated for cold engine starts. Application of the MicroPilot® system on the CAT 3412 genset engine proved to be more complicated than the CAT 3406. These challenges were investigated and solutions were proposed, but time and funding constraints resulted in this activity not being completed.

1.0 Introduction

This project was proposed to and contracted by the Commission, to GRI with a subcontract to BKM. Effective June 18, 2001, Clean Air Partners (CAP) has acquired BKM Business Development Corp (BKM). Clean Air Partners, through its license and business agreements with Caterpillar, develops and sells natural gas fueled Caterpillar engines worldwide. Additionally, CAP sells natural gas components, including injectors, worldwide. Since CAP's inception in 1992, BKM has provided all of the Company's engineering as well as component assembly, by contract.

Since the acquisition of BKM occurred during the term of this contract, and BKM no longer exists as a separate entity, we will generally refer to both entities as Clean Air Partners (CAP) in this report. In a few instances, we have referred to the organizations separately, for the purposes of clarity, for the time period prior to the acquisition.

1.1. Background and Overview

Environmentally Preferred Advanced Generation is broadly defined as RD & D activities targeting the development of highly efficient generation technologies using clean fuels. This project was proposed to develop a lube oil MicroPilot®, compression ignition, natural gas fueled generator engine. Since the pilot and gas injection systems are less complex than either a diesel or spark gas system, the MicroPilot® approach offers the best efficiency (over 38%) and lowest installed cost per kW (under $200 $/kW) of any engine in the power class under 5mW. Spark ignition natural gas engines typically have an installed cost near $400/kW. This emissions friendly engine technology will also significantly reduce the cost and the toxic environmental hazards associated with used engine oil disposal.

The goal of this project was to finish development and demonstrate "a high efficiency, low initial cost, low operating cost, low emissions natural gas engine for use in a deregulated, distributed power generation market in California (and elsewhere). This project was a continuation of research and development previously funded by the Gas Research Institute (GRI).

For distributed power generation to reach its true potential, the power must be produced at competitive costs, it must have low installation cost, it must be easily installed close to the end user and be in compliance with air quality standards and goals.

Natural gas is a very clean and cost competitive fuel and has successfully displaced coal and oil in many large power plant applications based on its cost and emissions benefits.

Under a regulated utility, cost-of-service model, there was incentive for electric utilities to purse significant technology development efforts beyond existing technology for diesel engines, and spark ignited gas engines or gas turbines. These three (3) technologies represent the most common approaches to distributed generation in those cases where inroads have been made on the central power plant approach (see GRI report 98/0025 published January 1998). With deregulation of the electric utility industry, however, opportunities for distributed power generation to eliminate the need for transmission and distribution system upgrades will become more prevalent.

GRI has been funding the development of a new technology that takes advantage of the cost and emissions benefits of clean burning natural gas, the fuel efficiency of modern diesel engines, the low first cost of high production diesel engines, and the ease of installing distributed power with an internal combustion engine.

This technology is known as MicroPilot® diesel cycle natural gas engines. This project was proposed to complete the development of a one percent MicroPilot® engine and demonstrate a production ready version of the MicroPilot® technology applied to the Caterpillar 3412 diesel generator set engine. In addition to development and demonstration of this highly cost competitive approach to distributed power generation, a concurrent effort to develop and optimize the lowest possible emissions was proposed, although, not funded.

This project proposed to complete certain performance development using the current Caterpillar 6 cylinder 3406 "proof of concept" engine and then transfer the technology to the more typical Caterpillar 12 cylinder 3412 generator set engine. Development testing for further performance enhancement and emissions reduction will continue using the Caterpillar 3406 test bed engine.

The compression ignition MicroPilot® has the best overall fuel efficiency (over 38 percent) and lowest overall operating cost (less than 4 cents / kW-hr) of any of the current common methods of locally produced distributed power. This technology also has the characteristic of an installed engine cost less than 50 percent of any current alternative. The addition of advanced methods for lowering emissions to acceptable levels makes this a very attractive benefit for California electric power consumers (reference GRI report 98 / 0025).

Clean Air Partners (CAP) was awarded Gas Research Institute (GRI) Contract No. 5094-290-2842 in May 1994. The project was to design, test and prove the concept of a MicroPilot®, diesel / natural gas fuel system derived from proprietary Servojet fuel system technology. The MicroPilot® diesel technology provides the low Nitrogen Oxides (NOx) emissions of a spark-ignited, lean-burn natural gas engine, with the high efficiency and power output of a diesel engine. A MicroPilot® engine is a dedicated natural gas engine with a diesel injector used for ignition rather than a spark plug. Retaining the time proven diesel injector as the ignition source, it changes how the engine burns fuel, from a typical spark-ignition combustion process to the more efficient compression ignition. The MicroPilot® principle has been demonstrated in laboratory tests initially using a 1986 Navistar DT-466 engine and later the Caterpillar 3406B Series engine. Natural gas substitution greater than 97 percent, at rated output, was achieved with NOx levels below 2 g / hp-h.

A second contract was awarded CAP, by GRI, in January 1996 to develop a stationary MicroPilot® natural gas engine demonstrating 2 g / hp-h NOx and 38 percent or greater thermal efficiency. Besides efficiency and emissions, the driving force of the project was to provide a natural gas generator set with very low first cost and with power and efficiency equal to the diesel counterpart. The engine selected for the development effort was the Caterpillar 3406 engine rated 400 hp at 1800 rpm, based on the following considerations:

1. Low base engine cost, using a new or remanufactured diesel engine.

2. Low specific cost ($200 / kW) due to higher ratings of the diesel engine relative to a heavy-duty spark ignition gas engine.

3. Low cost of combined electronic gas and diesel MicroPilot® injectors.

4. Low operating cost with diesel efficiency and extended overhaul life.

The MicroPilot® technology includes the following features:

- Lean burn combustion
- Unthrottled intake
- Timed port injection of gas
- Compression ignition of pilot diesel fuel
- Full time cycle-to-cycle electronic control of:
  - Air fuel ratio
  - Gas injection quantity and timing
  - MicroPilot® diesel quantity and timing

The MicroPilot® 3406 engine has demonstrated 2 g/hp-h NOx level and 38 percent thermal efficiency at rated conditions (1800 rpm, 400 hp) in the test laboratory. The overall performance is summarized as follows:

- Thermal efficiency based on diesel and natural gas lower heating-value matches the stock diesel baseline at a much lower NOx level, even at 25 percent load.
- Diesel fuel replacement is 98 percent at 100 percent load, and 97 percent at 25 percent load.
- THC emission level below 8 g/hp-h, representing approximately 0.6 g/hp-h NMHC at 50 percent load and greater.
- CO emissions are <2.0 g/hp-h, while NOx was maintained at 1 g/hp-h with the exception of the 25 percent load condition.

At part load conditions, the same specific emission levels have been achieved through full control of pilot and gas injection timings and the air/fuel ratio. CAP patented Skip-Fire (SF) technique and Turbo-Air-Bypass (TAB) device have proven to be very effective methods for controlling the air/fuel ratio and combustion characteristics at moderate and low load conditions. It is the SF and TAB that makes the two to three percent pilot fuel and high efficiency possible on an unthrottled, natural gas engine.

The stock diesel pencil-nozzle injectors were converted to electronically controlled pilot injectors delivering MicroPilot® fuel quantity (4-8 mm3/injection). It was demonstrated that the pilot injector spray jets have significant ignition energy and are capable of widely spreading over the combustion chamber. The small quantity injected is quite adequate to ignite air/gas mixtures up to an excess air ratio of two. Further reduced pilot delivery was not explored due to time and budget limitations; however, it was concluded that with special pilot injectors, scaled down in size, pilot quantities can be reduced to one percent at rated power.

1.2. Production Readiness Plan

1.2.1. Introduction

The production readiness plan was not part of the proposed scope of work or budgeted for, in this project. GRI and CAP developed the production readiness plan at the initiation of the project, and the Commission accepted it. There was no budget to update the plan as work progressed and as the business environment evolved.

1.2.2. MicroPilot® Production Readiness Plan

The MicroPilot® fuel systems and engines proposed in this project are based on existing or similar components as far as critical production processes, equipment, facilities, manpower, and support systems needed to produce a commercially viable product.

Standard production diesel engines from Caterpillar typically used in power generation applications will be used for both the development project and commercialization of this new technology. The engines will be manufactured on the normal production line; they will simply be assembled without the standard diesel fuel injection system (fuel pump, injectors, lines, ancillary equipment, etc.).

The natural gas injection portion of the MicroPilot® system is very similar to the electronic dual fuel systems offered by Caterpillar as an option on their on highway truck engines. The production processes, equipment, facilities, manpower and support systems are in place and in production for all of the components, which make up those natural gas fuel systems. All of the same suppliers currently producing these natural gas fuel system components will be the suppliers for the MicroPilot® components.

The unique part of these engines will be the ignition system. Unlike virtually all other gas engines used for power generation, this technology uses a very small injection of liquid fuel (diesel, engine oil, etc.) as the ignition source. This very small injection of liquid fuel is called a pilot injection. For the purpose of this project we call this very small pilot injection “MicroPilot.” For commercial purposes, Clean Air Partners has applied for trademark protection for the MicroPilot® product name.

The liquid fuel injectors used for the very small injection quantities are derived from standard diesel fuel injectors found on all commercial diesel engines. Several manufacturers of diesel fuel injectors and diesel fuel injection equipment have expressed an interest in becoming the production source for the MicroPilot® injectors. Prototype injectors have successfully been produced before for earlier stage development of this technology involving larger flow injectors of the same basic design. There are no known critical production processes, equipment, facilities, manpower or support systems needed to produce this product commercially as a viable product. The only challenging task is producing the very, very small holes in the injector tips – nearly 10 times smaller than typical diesel injectors are. Small hole production has been accomplished in other industries and was performed successfully in earlier stage development of this MicroPilot® technology.

As stated earlier, the base engines and the natural gas portion of the fuel systems proposed in the project are currently in production. There are no known capacity constraints imposed by the design. There are several sources for the liquid fuel injectors, most of which produce diesel fuel injectors in quantities well over 500,000 units per year. The natural gas injectors are currently tooled to produce over 25,000 per year even though annual volumes are currently 6,000-10,000 per year - increasing capacity is very easy. Caterpillar produces nearly 100,000 engines per year between their truck engine business and their industrial engine business. Caterpillar can easily increase capacity for the base engines considered by this project.

One of the most appealing aspects of MicroPilot® is the potential to be very cost competitive with conventional diesel generator sets from both a first cost and operational cost basis (not to mention the much lower exhaust emissions). The projected "should cost" is a total MicroPilot® generator set engine retail price at a premium of 0-30% as compared to the same kilowatt rating as a conventional diesel engine. Current spark ignited dedicated engines commonly cost 100% more per kW than a diesel.

The largest single investment required to launch this commercial product is the development, durability testing and demonstration costs. GRI has invested over $1,000,000 prior to this project in the proof of concept work required up to this point. With the concept established as viable and the technical results considered quite compelling, this Commission / GRI project will complete the development, provide the durability testing and demonstrate the products.

The next most significant investment will be the cost of packaging and integrating the MicroPilot® into commercial generator set packages. This technology is so similar to standard diesel engine packages there is very little investment required in order to complete the engineering necessary to address the unique items.

The final investment will be the marketing effort. This product will be marketed, distributed and serviced through the existing Caterpillar dealer network that currently sells the diesel generator products. There is virtually no incremental investment required in this area.

There is no need for a complex, comprehensive implementation plan in order to ramp up to full production. The existing suppliers for the base engines and the natural gas fuel systems will simply have their purchase order quantities increased. The supplier of the equipment unique to the MicroPilot® injection equipment will simply need a purchase order to produce product. The lead times associated with developing and closing a sale for distributed power generation applications often requires months, the lead times to produce the MicroPilot® engines is only 8 to 12 weeks. Production readiness is not an issue once development is completed and the sales force begins selling.

1.3. Project Objectives

This project was intended facilitate the earliest introduction of the MicroPilot® technology to field service. The goal was a genset package having diesel efficiency and with less than (<) 2g / hp-h NOx. Simultaneously, research was conducted to reduce the NOx level to < 1.5 g / hp-h maintaining or improving the thermal efficiency demonstrated with the 2 g NOx version. These improvements were expected from efforts of optimizing the combustion chamber and pilot injector spray characteristics using methodology developed by CAP.

Additionally, the utilization of lube-oil as pilot-fuel would be explored determining performance and emission characteristics. This practice would eliminate the need for oil changes thereby reducing maintenance costs. The successful use of lube-oil greatly depends on the quantity of pilot fuel, generally preferred to be less than 1% of the total fuel requirement.

The final goal is the technology transfer to the CAT 3412 engine used more extensively for power generation.

The specific technical objectives upon which this project's success will be evaluated are:

- To test and develop a CAT 3406 genset package with 2% MicroPilot® technology having 38% thermal efficiency or better with < 2g / hp-h NOx.
- To test and develop a CAT 3406 genset package with 1% MicroPilot® technology having 38% thermal efficiency or better with < 1.5g / hp-h NOx using lube oil as the pilot fuel.
- To transfer both the 2% and the 1% MicroPilot® technology to a CAT 3412 engine genset package, followed by troubleshooting unique 3412 problems. The goals for the CAT 3412 with MicroPilot® are 38% thermal efficiency or better with < 2.0 g / hp-h NOx.
- To do durability testing on the CAT 3412 engine genset using the MicroPilot® technology. The goals for this test are 38 % thermal efficiency or better at < 2.0 g / hp-h NOx before and after the equivalent of 1000 hours of testing with 80 % of the time at 60% load and 20% of the time at 100% load.

1.4. Report Organization

This report is organized to follow the four tasks contracted for this effort and described in the next section. For each task, the objectives, plans and results will be discussed.

2.0 Project Approach

A four phase research and development programs was proposed, with Phase 1 funded in this program. The un-funded remaining phases focused on In-Cylinder Emissions Reduction (Phase II), Emissions Reduction Using after Treatment (Phase III) and Combustion System Optimization (Phase IV).

Phase I was funded by the Commission and focused on the development of a CAT 3412 Genset with one percent MicroPilot® lube oil injection, demonstration project. This phase will start with the CAT 3406 (6 cylinder) Genset Engine used in a previous project to demonstrate proof of concept. This base engine will be used to develop the one percent pilot injection hardware and software, and lube oil injection system. Once this work is complete (Tasks 2.1 & 2.2), the hardware and software will be scaled and modified for the 12-cylinder version, the CAT 3412 Genset Engine. The system will be performance and durability tested on the CAT 3412 Genset in Tasks 2.3 & 2.4.

The plan for the four technology development tasks was:

2.1. CAT 3406 Genset Engine - 2% MicroPilot® fuel injection

2.1.1. Task Objective

The objective of this task is to develop and test the CAT 3406 engine genset on a test cell with the two percent MicroPilot® fuel system operating on diesel fuel. Durability testing will also be conducted on the two percent MicroPilot® system. The engine test cell will be the basis for the work in Task 2.2 evaluating lube oil as a MicroPilot® fuel and the one percent MicroPilot® injectors.

2.1.2. Task Activities:

a) Build components, calibrate software, and install the two percent MicroPilot® fuel system on the CAT 3406 engine.

b) Develop genset specific (control) software.

c) Test and develop two percent MicroPilot® genset operation and performance.

d) Durability Testing of the two percent MicroPilot® System

2.1.3. Measurement of Completion/Success

Complete durability testing of the CAT 3406 with the two percent MicroPilot® fuel system for 20 hours at full load and 80 hours at 60 percent load and met NOx emission levels of less than 2.0 g/hp-hr and 38 percent thermal efficiency at rated conditions **(**1 hour rating – of 400 hp @ 1800 rpm). Develop an engine genset test cell that is fully capable of testing the one percent MicroPilot® system and have evaluated the use of one percent lube oil for MicroPilot® operation

2.2. CAT. 3406 Test Cell Engine - 1% MicroPilot®

2.2.1. Task Objective

The objective of this task is to design and fabricate the one percent MicroPilot® fuel system; followed by testing of the system on the CAT 3406 test cell developed in Task 2.1. One percent lube oil will also be evaluated as a pilot fuel for MicroPilot® operation.

2.2.2. Task Activities

Design & develop the one percent MicroPilot® fuel system by computer modeling to achieve the best spray characteristics.

Fabricate one percent MicroPilot® injectors based on computer model results, bench test and calibrate the system, and install the one percent MicroPilot® system on the test engine.

Develop and test the one percent MicroPilot® system for performance and durability.

Evaluate one percent lube oil MicroPilot® operation.

2.2.3. Measurement of Completion/Success

Develop and test the one percent MicroPilot® system with the intentions of operating at <1.5 g/hp-h NOx at 38 percent or better thermal efficiency at rated conditions (400 hp @ 1800 rpm, one hour rating) using lube oil as the pilot fuel.

2.3. CAT 3412 Genset with the 2% MicroPilot® system.

2.3.1. Task Objective

Purchase and modify the CAT 3412 Genset to operate with the MicroPilot® system.

2.3.2. Task Activities

a) Purchase CAT 3412 Genset for field service.

b) Fabricate additional MicroPilot® injectors and design the other components required for the CAT 3412 Genset, install MicroPilot® fuel system.

c) Expand control software for 12-cylinder operation.

d) Install Genset in CAP's test cell area.

e) Initial engine testing and troubleshooting.

2.3.3. Measurement of Completion/Success

The CAT 3412 genset using MicroPilot® injectors will be completely assembled and installed in the CAP test cell. The test cell will be modified to accept the Genset. All software and hardware will be debugged and ready for optimization of the Genset

2.4. CAT 3412 Genset Engine MicroPilot® Durability Test

2.4.1. Task Objective

The goal of this task is to successfully demonstrate the durability of the low-emission, high-efficiency operation of the CAT 3412 engine genset using MicroPilot® injectors.

2.4.2. Task Activities

a) Validate engine emission and efficiency levels and software stability. Finalize software calibration.

b) Place CAT 3412 Genset with the MicroPilot® system in a location for evaluation of durability.

2.4.3. Measurement of Completion/Success

The genset will be optimized to run at 38 percent thermal efficiency at 100 percent load and 2.0 g/hp-hr BSNOx. It will then operate for 340,000 kW-hr (the equivalent of 1000 hours with 80 percent of the time at 60 percent load and 20 percent of the time at 100 percent load, with 100 percent load being 500 kW). NOx emissions testing will be conducted at the beginning and the end of the test to determine if there is any emission performance degradation.

3.0 Task Report 2.1: Development of a 2% MicroPilot® Fuel Injection System for the CAT 3406 Genset Engine

3.1. Introduction

This Task 2.1 Report describes the implementation and testing of the MicroPilot® dual fuel (diesel / natural gas) system installed on a CAT 3406 Genset. The system was designed and fabricated for the 3406 Engine under prior GRI contract number 5090-290-2842. That hardware and experience was then applied to the 3406 Genset for this project.

3.1.1. Project Objectives

The objective of this task is to develop and test the CAT 3406 engine genset on a test cell with the two percent MicroPilot® fuel system operating on diesel fuel. Durability testing will also be conducted on the two percent MicroPilot® system. The engine test cell will be the basis for the work in Task 2.2 evaluating lube oil as a MicroPilot® fuel and the one percent MicroPilot® injectors

3.2. Work Plan

a) Transfer existing two percent MicroPilot® Technology to Genset Engine

b) Instrument Genset System

  i) Start Debugging

c) Place Genset on test Pad and Connect to Load Bank

d) Develop Genset Specific Software

  i) Modifications for governor

  ii) Test on running engine

e) Develop engine and systems performance

f) Evaluate durability of two percent system

3.3. Test Plan

3.3.1. Initial Startup and Testing

This phase of the testing is to verify that the engine and its associated equipment works correctly.

3.3.2. Emissions and Efficiency Optimization

The 60 percent and 100 percent load points need to be optimized for greater than 38 percent thermal efficiency and less than 2 g/hp-h NOx.

3.3.3. Sixty Percent Load, Eighty Hours

Run the engine for 80 hrs at 60 percent load with regular monitoring of fuel consumption and emissions.

3.3.4. One Hundred Percent Load, Twenty Hours

Run the engine for 20 hrs at 100 percent load with constant monitoring of fuel consumption and regular emissions testing.

3.4. Test Cell

3.4.1. Trailer

The engine and generator are mounted in a sound attenuated trailer parked on the north side of BKM (Figure 1).

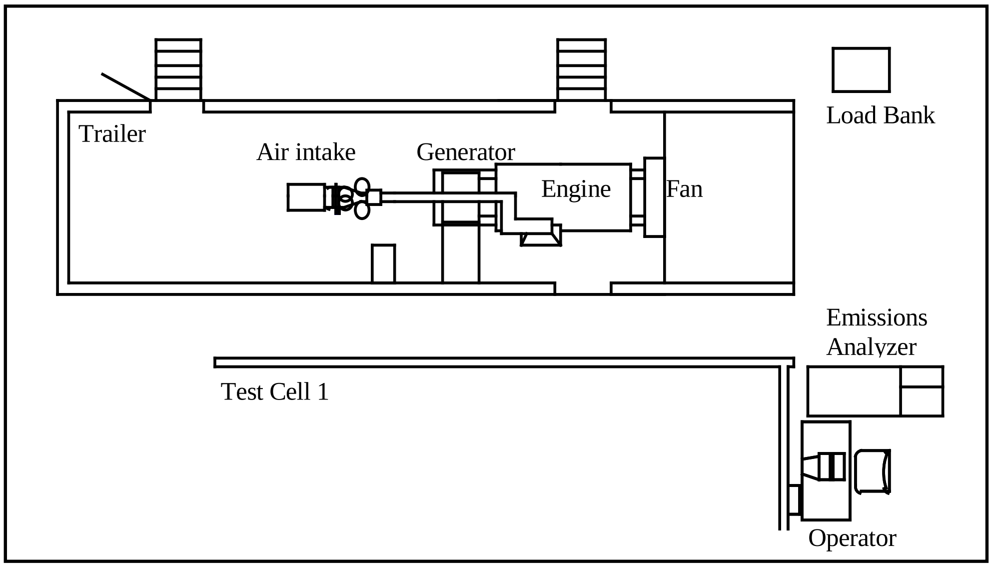


Figure 1. Genset Trailer Layout

3.4.2. Load Bank

Two resistive load banks were used for testing, one a 225 kW and the other a 300 kW, both provided by Alturdyne. The resistive load is adjustable by switches on the side of the unit. Six 4/0 AWG copper wires attach to the three phases (two to each phase) and one wire attaches to ground. In addition, the load bank requires a 110 or 220 VAC to power its internal cooling fan.

3.4.3. BKM-DAQ

BKM-DAQ is a PC based Data Acquisition system that consists of BKM proprietary software coded in National Instruments LabView G programming language. The hardware is a National Instruments PCI data acquisition card and SCXI terminal block, attached to BKM designed interface panel. Fifteen thermocouples, nine pressure sensors, three load sensors, three emission analyzers, one air flow meter and one speed sensor connect to the interface panel. These inputs are sampled continuously (4 samples per minute recorded) with the data acquisition program for engine monitoring and used to obtain values for thermal efficiency and brake specific emissions.

3.4.4. Beckman Emissions Analyzer

The Beckman Emissions Analyzer consists of three separate analyzing units that measure Nitrous Oxides (NOx), Hydrocarbons (HC), and Carbon Monoxide (CO) in units of parts per million (ppm). This project is primarily concerned with the NOx analyzer, which is the Beckman Model 951 NO/NOx Analyzer. The analyzer utilizes the chemiluminescent method of detection to determine NOx concentration in the exhaust stream. Combined with information from the DAQ, ppm is converted to grams per horsepower-hour (g/hp-h).

3.5. CAT 3406B

3.5.1. Engine Specifications

Table 1 shows the engine specifications.

Table 1. CAT 3406B Engine Specifications

Bore	137 (5.4) mm (in)
Stroke	165 (6.5) mm (in)
Displacement	14.6 (893) L (cu in)
Compression Ratio	14.5:1
Configuration	Inline 6
Aspiration	Turbocharged with air-to-air after cooler
Power	400 hp
Rated Speed	1800 rpm

The MicroPilot® system has been installed on a CAT 3406B diesel engine (Figure 2 and 3). An aftermarket Air-to-Air heat exchanger was added to reduce the air charge temperature, in addition to the MicroPilot® diesel and gas hardware.

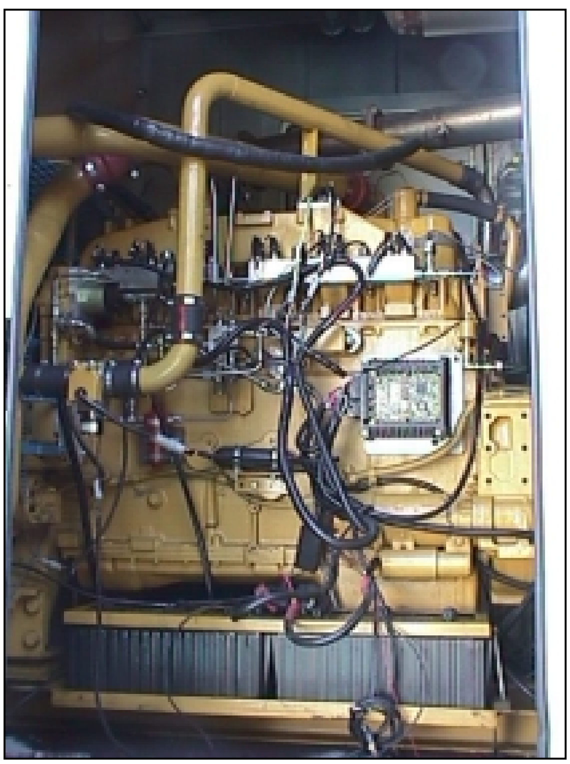


Figure 2. Left Side of the Engine as Installed in the Trailer ECU installation can be clearly seen on the side of engine.

Figure 3. Left Side of Engine with Generator in Foreground

3.5.2. Generator Specifications

The power is generated by a CAT SR4B single bearing, wye connected, static regulated, brush less, self excited generator. The generator operates at 60 Hz (when engine is running at 1800 rpm) and 480 Volts. It can generate up to 400 kilowatts of continuous three-phase power, depending on the engine power. In our configuration 265 kilowatts of power is generated.

3.6. Two Percent MicroPilot® Fuel System

3.6.1. Fuel Supply System

The MicroPilot® fuel system uses two fuel pumps to provide diesel to the injectors. The first pump is an electric Mallory 250 transfer pump that primes the Servojet RV-4 pump. The RV-4 pump is a positive displacement pump and is mechanically driven in the auxiliary power unit (APU) drive location. The RV-4 provides high pressure (up to 2000 psig) diesel fuel to the common rail (Figure 4).

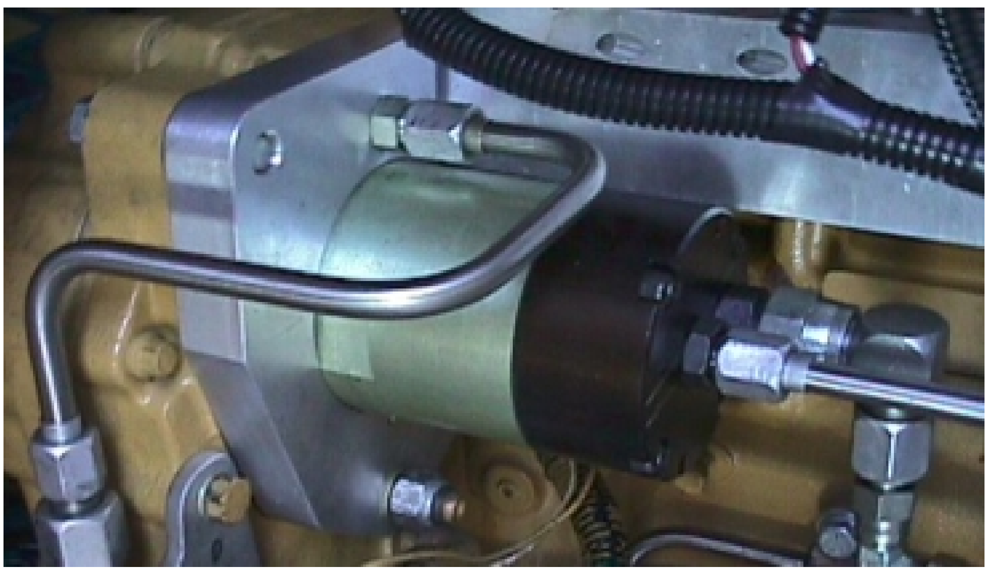


Figure 4. Photograph of RV-4 Fuel Supply Pump
This view shows the RV-4 pump installed in the auxiliary drive. Inlet, outlet and relief lines are visible.

3.6.2. EPR Block

The electronic pressure regulator (EPR) Block regulates the pressure of the common rail (Figures 5 and 6). Varying the rail pressure controls the injection quantity. To vary the rail pressure, a Wandfluh two-way solenoid valve is actuated with a modulated pulse. Increasing pulse width increases the time the Wandfluh is closed and increases the pressure of the diesel rail.

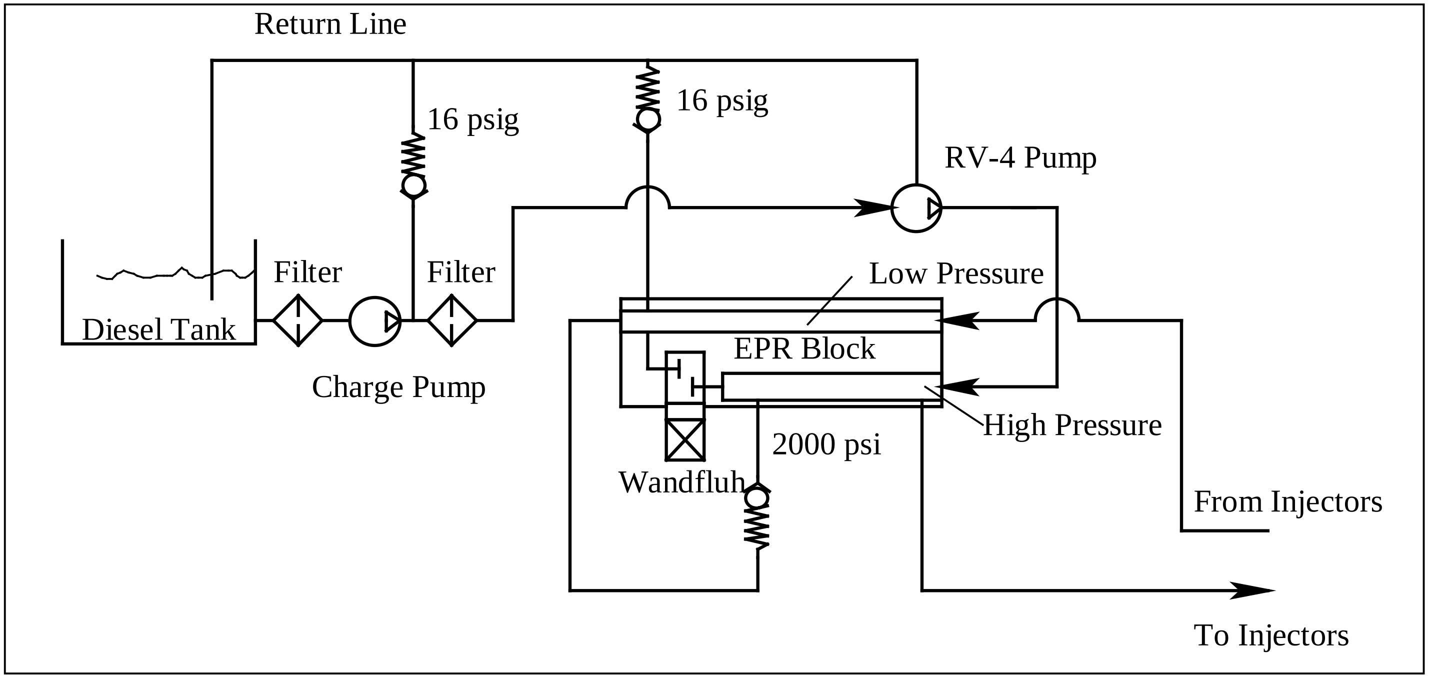


Figure 5. Schematic Design of the EPR Block and MicroPilot® Fuel Supply System
The fuel supply system closely regulates high pressure to the injectors to allow for consistent fuel delivery

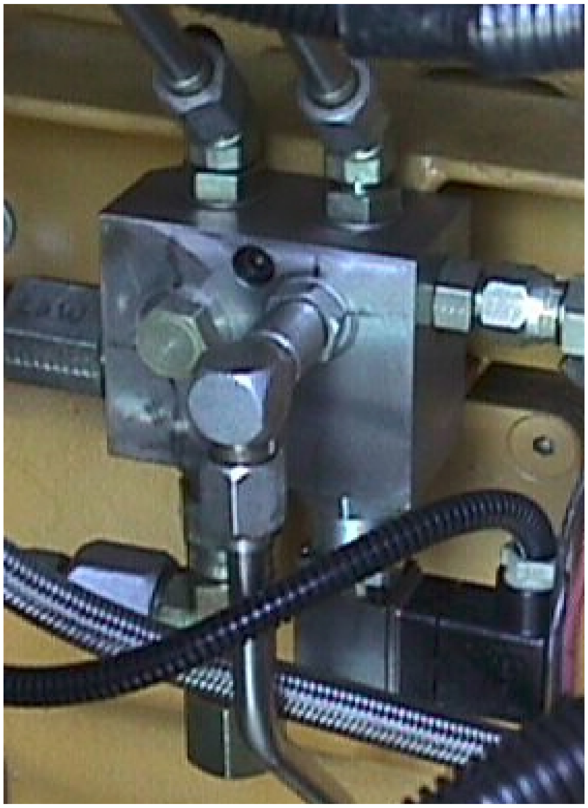


Figure 6. EPR block, with Wandfluh Control Valve Attached to Bottom High and low pressure lines connect to top surface.

Figure 7. Common Rail Diesel System with Inlet (High Pressure) and Vent (Low Pressure) Lines

3.6.3. Common Rail

MicroPilot® uses remote mounted intensifiers on a common rail to increase diesel pressure coming from the RV-4 pump by a factor of four before reaching the injectors (Figure 7). The intensifiers also incorporate a Servojet solenoid valve to actuate the injector. The common rail consists of two separate metal manifolds that contain the high and low pressure diesel fuel passages, plus the location for a diesel rail pressure transducer.

3.6.4. MicroPilot® Injectors

MicroPilot® injectors are stock pencil type injectors that have been modified to work with a peak injection pressure of 4,800-8,000 psig and injection duration of less than 1 millisecond. This results in an injector that operates in the range of 4.5~8mm^3 per injection, or 2~4% of maximum fuel (Figure 8 and Figure 9). The MicroPilot® injectors have four equally spaced 0.15 mm diameter holes in the tip.

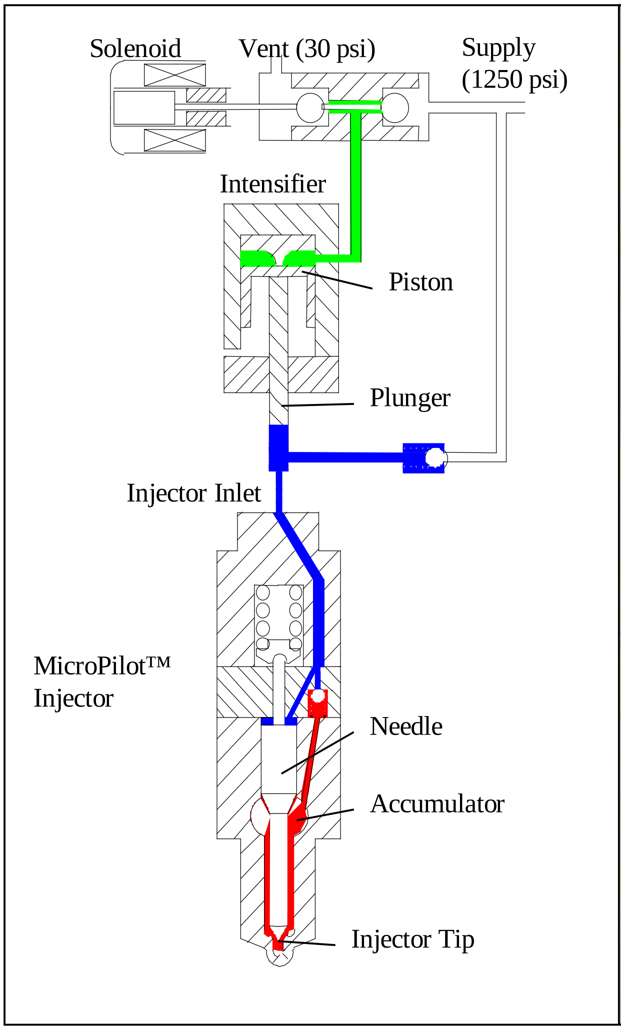


Figure 8. Schematic of MicroPilot® injector and intensifier

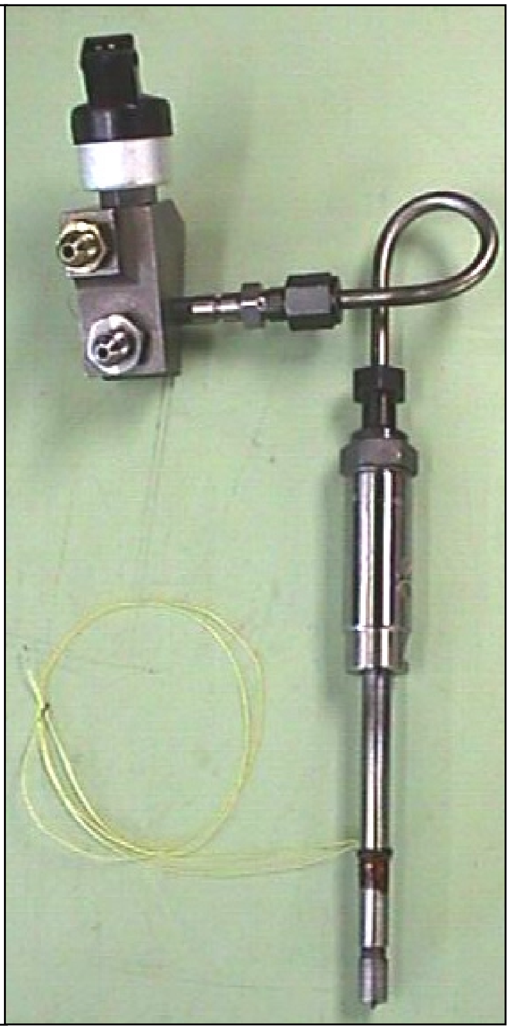


Figure 9. Photograph of MicroPilot® injector and intensifier

3.6.5. The Natural Gas System

The MicroPilot® system uses port injected compressed natural gas (CNG) as the primary fuel source. The Natural Gas System consists of a 100 psig CNG inlet line, two safety shutoff valves, and 12 Servojet SP-010 gaseous fuel injectors. The ECU gives a 5-20 ms pulse to the gas solenoid valve depending on the fuel commanded. Two gas valves inject gas into the manifold directly upstream of each intake port.

3.6.6. Electronic Control Unit (ECU)

The ECU is a BKM designed unit that controls all of the electronic equipment on the engine. Inputs to the ECU are:

- CNG pressure
- CNG temperature
- Manifold air pressure (MAP)
- Air charge temperature (ACT)
- Engine speed
- Diesel rail pressure
- Speed commanded

The ECU uses a programmable set of algorithms to determine the proper outputs for a given set of inputs. These outputs are:

- CNG injector pulses (timing and duration)
- Diesel injector pulses (timing and duration)
- Duty cycle of the electronic pressure regulator (to control diesel rail pressure)
- CNG safety shutoff valve control
- Duty cycle of Turbo Air Bypass (TAB) valve (to control manifold pressure)

The ECU uses electronically programmable read-only memory (EPROM) to store the software program that the CPU executes. This allows for easy software upgrades during development. In addition the ECU is able to communicate with an IBM Compatible PC, via the serial interface. BKM developed software is then able to communicate directly with the ECU during operation to monitor operating conditions and change operating parameters.

3.6.7. Air/Fuel Ratio Control

The MicroPilot® 3406, unlike the diesel 3406 is a lambda (normalized air-to-fuel ratio) controlled system. With a diesel engine, lambda is kept as lean as possible because compression ignition with direct injection will allow all fuel to be burned as long as there is enough air. Any non-direct injection system (port injection, throttle body injection, carburation) requires control of air flow into the engine to prevent misfire when reaching the lean limit. Air flow is typically controlled with a throttle, but they cause significant restrictions in air flow when full wide open. The MicroPilot® system uses a turbo air bypass valve to achieve the same lambda control, but without the losses.

3.6.8. Turbo Air Bypass

The turbo air bypass (TAB) is a duty cycle controlled butterfly valve placed downstream of the turbo and aftercooler, but before the intake manifold. The TAB valve vents air pressure from the manifold and returns it upstream of the turbo. By controlling the manifold pressure with the TAB valve, the air fuel ratio of the engine may be adjusted for optimum performance (Figures 10 and 11).

Figure 10. Turbo-Air-Bypass valve before installation.

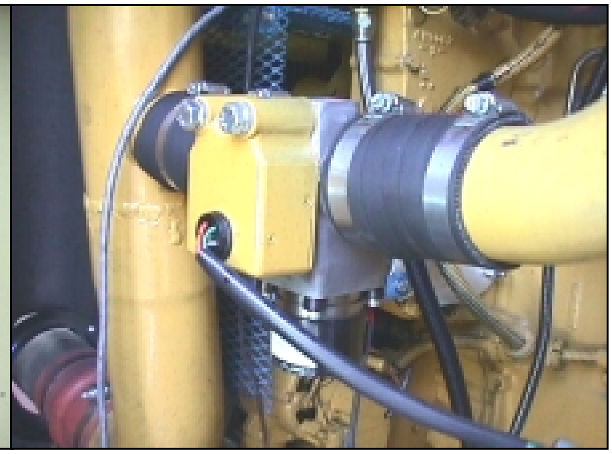


Figure 11. Turbo-Air-Bypass valve installed on engine.

3.6.9. Genset Control Software

The generator uses an all-speed-governor and PID controller to determine quantity of fuel injected. Due to the generator application, the control software is optimized for rated speed (1800 rpm) at 60 percent to 100 percent load. An important feature of the genset control is fuel limiting. Situations can arise when the engine fuel requirements exceed knock limits and the controller would demand enough gas to cause knock. It is for this reason that the controller is designed to limit fuel by airflow. Since airflow is dependent on MAP, the fuel limit is simply referenced to boost pressure. For a complete description of the genset control software, see Appendix II, Genset Control Flowchart.

3.7. Operational Parameters and Performance Characteristics

3.7.1. Kilowatts and Horsepower

The project requirements for the 3406 Genset refer to a 400 horsepower engine. This is engine shaft power, and cannot be directly measured (as on an engine dyno). The only measurable quantity is the power the generator delivers to the load bank. Assuming a parasitic power loss of 20 hp (from engine fan, fuel pump and generator fan) and a generator efficiency of .93, the engine shaft horsepower can be calculated from the kilowatts of resistive usable power. Any horsepower rating documented in this report refers to engine shaft power and any kilowatt rating refers to usable power to a resistive load. Resistive load was calculated using current and voltage probes and a power factor of 1. The 60 percent load point is based on 60 percent of max engine shaft horsepower. Therefore, 60 percent load is 240 horsepower (100 percent load is 400 horsepower). However, parasitic losses are independent of load so 100 percent engine horsepower corresponds with 265 kW, and 60 percent engine horsepower produces 154 kW (58 percent of max kW).

3.7.2. Operational Parameters

Table 2 shows genset operating conditions.

Table 2. CAT 3406 Genset Operating Conditions

Speed	0-2200 rpm
Load	0-400 hp
Pilot Timing	8-14 °BTDC
CNG Timing	230 °BTDC
Diesel Rail Pressure	1350 psig
Diesel Pilot Quantity	5.0 mm^3 (2.25%)
CNG Pressure (EOI)	90-120 psig
Inlet Air Temp	60-100 °F

3.7.3. Performance Characteristics

The MicroPilot® genset was designed to perform similarly to the CAT 3406 diesel genset (shown in Table 3.

Table 3. MicroPilot® 3406 Genset Operating Conditions

Rated Speed	1800 rpm
Max Engine Power	400 hp
Max Generator Power	265 kW
MAP	101-220 kPa
ACT	20-60 °C
Exhaust Cylinder Temp	150-550 °C
Lambda Gas	2.05
Thermal Efficiency	>.38
BSNOx	< 2 g/hp-h

3.7.4. Pilot Timing Shift

The key to being able to meet NOx and Thermal Efficiency numbers over varying load is a pilot timing shift and adjusting air / fuel ratio. Under fixed timing and air / fuel ratio conditions, thermal efficiency and NOx increase with load. With the same timing and air / fuel ratio as the 60% load point, the engine would produce considerably more than 2.0 g / hp-h NOx, and have more than 38% thermal efficiency. By retarding the pilot timing and richening the air / fuel ratio (as compared to 60% load point), the genset is able to meet the target emissions and thermal efficiency at full load. The ECU actively adjusts timing and air / fuel ratio, as a function of load (fuel flow) to achieve the target emissions and efficiency.

3.8. Durability Test Results

3.8.1. Eighty Hours at 60% load

The durability test was run November 2, 1999, through November 17, 1999 at the BKM test facilities. Results of the 60percent load endurance test are as follows:

- Average NOx=1.66 ± 0.27g / hp-h
- Average Thermal Efficiency = 38.0 ± 0.4%

The engine passed the test with no major problems. Detailed results can be found in Appendix I-1.

3.8.2. Twenty Hours at 100% load

The 100 percent durability test was run November 29 through December 2. Results from the 100 percent endurance test are as follows:

- Average NOx=1.69 ± 0.25g / hp-h
- Average Thermal Efficiency = 38.1 ± 0.1 percent

The test was completed with no major problems. Detailed results can be found in Appendix I-2.

3.9. Problems encountered

3.9.1. Fuel Pump Leak

The Servojet RV-4 fuel pump on the engine experienced difficulties several times during the development and testing of the two percent system. The fuel pump repeatedly leaked diesel though a seal on the impeller shaft. The pump seal was replaced several times, but it continued leaking, possibly due to a design related assembly problem. The pump was replaced with a previously assembled RV-4 pump, and the new pump did not leak.

3.9.2. ECU reset

The ECU occasionally experienced a phenomenon designated as reset during one phase of the testing. The ECU would stop communicating for an instant, reset itself and continue running. The engine RPM would drop slightly for just an instant under heavy loads, and then resume normal operation. The problem was attributed to too many events occurring simultaneously, essentially too much information for the processor to handle. The events cause a high speed output (HSO) buffer overflow, and the ECU resets. The solution was to adjust the timing of certain events to stop the buffer overflow.

3.9.3. Engine Overheat.

The coolant temperatures during the 100 percent load test were approaching high alarms (220°F) when the inlet air temperatures were high. The intercooler reduces the efficiency of the radiator and therefore limits the heat it can dissipate. An additional electric fan blowing across the radiator was added and the coolant temperature stayed within acceptable limits during the rest of testing.

3.9.4. Starting and Warm-up Issues

The engine is able to start normally but requires a 3-4 minute warm up period before the engine can accept load. Cylinder temperatures are uneven after startup until the engine warms up.

3.9.5. High Injector Tip Temperatures

Upon inspection of the MicroPilot® injector needle tips, it was determined that the needle tip temperatures reached points higher than suggested by Caterpillar. Examination of the needle tips after the durability test revealed blue-ish colored steel, indicating that the tip temperature had reached at least 550 °F [2]. This is a source of concern because Caterpillar rates the pencil injectors up to 400 °F, and warns about shortened lifetimes at higher temperatures. Regardless, the MicroPilot® injectors showed no sign of degradation after the 100 hour durability test.

3.9.6. Diesel Fuel Overheat

There was a diesel fuel and engine coolant overheating problem with the initial configuration. Originally, the vent line from the EPR block was being routed through an air to fuel cooler and then to the inlet of the RV-4 pump. This configuration allows for a small transfer pump to supply diesel to the RV-4 pump, because excess fuel is cooled and re-circulated. During initial testing both the diesel fuel and engine coolant were high (100°F and 220°F respectively). Upon investigation, it was determined that the fin density of the fuel cooler was too restrictive. Since the radiator was down stream of the fuel cooler, a portion of the radiator's airflow was blocked. This resulted in the high coolant temperatures (220°F) at light loads (160 kW).

The system was redesigned to eliminate the need for the fuel cooler. This required replacing the transfer pump with one with greater capacity and plumbing the vent line from the EPR block back to the large (600 gallon) diesel tank. This corrected the overheating problem because the diesel tank was such a large heat sink that the diesel temperature never exceeded 65°F.

3.10. Conclusions

The 3406 two percent genset engine survived the durability test while meeting the project objectives for pilot quantity, emissions and thermal efficiency.

- The genset was optimized to run at the following conditions:
  - NOx < 2.0 g/hp-h
  - Thermal Efficiency > 38%
  - Pilot Quantity 5.0 mm3 (2.25%) diesel per injection.
  - 80 hrs at 60% load (154 kW)
  - 20 hrs at 100% load (265 kW)
- Emissions and thermal efficiency goals were met through the following strategies:
  - Optimized gas lambda with TAB valve air/fuel ratio control.
  - Minimized pilot quantity through calibration and testing
  - Optimized pilot timing through testing and NOx / Thermal efficiency tradeoff.
- The Engine was started and ran on 8.0 mm^3 lube oil per injection.

- The genset achieved the goal of low initial cost per kilowatt by the following strategies:
  - No cylinder head modifications were required.
  - Stock diesel injector (with modifications) was used for pilot injection.
  - Continuous rating of 265 kW was achieved.

3.11. Recommendations

Additional software upgrades are required before the MicroPilot® system can be placed in service for additional testing and durability. These upgrades include:

- Automatic starting and stopping routines.
- Complete integration of ECU with generator control panel.
- Speed governor upgrades to accept sudden load changes on lube oil.

Initial lube oil tests have shown that a smaller fuel pump driven with an electric motor is able to supply the same amount of rail pressure and fuel quantity for operation. This configuration should be investigated further due to the benefits of better starting, easier installation and lower cost.

4.0 Task Report 2.2: Development of a 1% Lube Oil MicroPilot® Fuel Injection System for the CAT 3406 Generator Set Engine

4.1. Introduction

This report describes the implementation and testing of the MicroPilot® one percent dual fuel (lube oil / natural gas) system installed on a CAT 3406 Generator Set (genset). The system was originally a diesel / natural gas two percent MicroPilot®, and the injectors were modified for one percent lube oil use.

4.1.1. Project Objectives

The objective of this task was to design and fabricate the One percent MicroPilot® fuel system; followed by testing of the system on the CAT 3406 test cell developed in Task 2.1. One percent lube oil was also evaluated as a pilot fuel for MicroPilot® operation.

4.2. Work Plan

a) Design and develop 1% MicroPilot® fuel system with computer modeling

b) Fabricate new injectors and lube oil fuel supply system.

c) Transfer new 1% MicroPilot® Technology to 3406 genset Engine

d) Develop Lube Oil Specific Software

   i) Fuel delivery calibration

   ii) Engine tests

f) Develop engine and systems performance

g) Evaluate feasibility of lube oil system.

h) Evaluate durability of 1% system

i) Report results

4.3. Test Plan

4.3.1. One Percent Lube Oil Injector Calibration and Testing

The new one percent lube oil injectors were calibrated and tested to ensure consistency and quality. In the course of the testing with the MicroPilot® fuel injector, it is necessary to adjust and document the calibration of the injector. The relationship between system settings, such as supply rail pressure, internal accumulator volume, needle closing pressure, needle lift and solenoid valve dwell time, affect calibration.

The pressure history of the MicroPilot® injector is essential to calibration. This pressure is observed using an injector mounted strain gage, which monitors the hoop stress in the injector body, thus giving a direct correlation of pressure versus time.

4.3.2. Emissions and Efficiency Optimization

The 60 percent and 100 percent load points need to be optimized for greater than 38 percent thermal efficiency and less than 1.5 g / hp-h NOx.

4.3.3. Sixty Percent Load, Eighty Hours

Run the engine for 80 hrs at 60 percent load with regular monitoring of fuel consumption and emissions.

4.3.4. One Hundred Percent Load, Twenty Hours

Run the engine for 20 hrs at 100 percent load with constant monitoring of fuel consumption and regular emissions testing.

4.4. Computer Modeling Results

4.4.1. Fuel Injector Design

The MicroPilot® system uses a diesel common rail with electronically governed diesel fuel pressure. The stock CAT pencil type injector body, nozzle and needle are modified and a hydraulic intensifier and solenoid actuated valve for each injector is added for control. These MicroPilot® modifications from Task 2.1 resulted in an injector that injects diesel fuel (or lube oil) at quantities of 4.4 mm^3 (2%) to 8 mm^3 (4%) and peak injection pressure of 5000 psi to 9000 psi. Once modified to MicroPilot®, delivery can be simplified to the following formula.

$$Q = \frac{V_{acc}}{K}\left(P_{\max} - P_c\right)$$

Where Q is delivered quantity of fuel per injection, K is a constant (determined by injector geometry, fuel bulk modulus, viscosity, etc), V_{acc} is accumulator volume, P_{max} is maximum accumulator pressure and P_c is accumulator closing pressure. Minor modifications to injector geometry (reduced needle seat diameter, reduced max needle lift) created an injector that delivered in the 3-4 mm^3 range.

In order to reduce delivery further, either V_{acc} or P_{max} must be reduced or P_c must be increased. P_{max} is strictly a function of diesel rail pressure and intensifier ratio. P_c was increased by increasing spring preload with shims. V_{acc} was reduced by use of filler pieces. A sleeve was installed in the inlet hole feeding the nozzle and the needle was unilaterally hard crome plated to reduce clearance between nozzle and needle. These final modifications resulted in an injector that could deliver between 2.0 mm^3 (1%) and 5.0 mm^3 (2%) and peak injection pressure of 4800 psi to 8500 psi.

4.4.2. Fuel Injection Simulation (FIS)

Before the two percent injector was modified to one percent and installed on the engine, a computer based Fuel Injection Simulation (FIS) program was run to model the one percent injector characteristics. The FIS program was used to theoretically simulate this injector and was compared to physical calibration results. This FORTRAN based program provides time based graphical results of pressures, motions and flow rates for critical areas within the system. This tool may be used for predicting injector performance and for identifying potential imperfections in system design or operation prior to fabrication and testing.

This one-dimensional mathematical model describes the flow inside the high-pressure lines and passages inside the injector. The flow is considered transient, isentropic and compressible. Two source equations are applied: conservation of momentum and conservation of mass. This approach distinguishes between forward and reflected pressure waves and their tracking along the line. Pressure loss in the line is modeled as Darcy-Weisbach hydraulic friction or, optionally, is based on an experimentally obtained correlation. Pressure histories inside concentrated volumes are obtained from mass conservation. Short high pressure lines are considered as concentrated volumes.

Fuel leakage throughout the fuel system is an essential phenomenon which effects system performance. Leakage through narrow annular gaps such as at the pump plunger, from control volume back to plunger volume and from plunger volume to crankcase, has been modeled. Leakage across the needle stem is also included. The dynamics of moving parts are obtained by solving the equations based on the equilibrium of forces acting on each part. In general, the forces include: inertia, friction, spring forces, pressure forces, and magnetic forces. Friction is modeled as hydraulic friction and springs are considered as linear elements. Density, bulk modulus, viscosity, sonic velocity, and surface tension of the fuel are considered as pressure and temperature dependent. The actual values are updated at each computational time step. The onset of fuel cavitation inside the plunger volume is calculated and depends on fuel temperature and supply valve opening pressure. Fluid boundaries are considered to be infinitely rigid. Motion of mechanical components is assumed non-oscillatory except for the needle valve, where an option for oscillatory contact was provided. The nozzle flow discharge coefficient is assumed to be needle lift dependent. A lumped parameter model, in which the magnetic field is represented by an equivalent magnetic circuit, used to calculate the solenoid magnetic force at the control valve. The electric circuit (control valve driver) is not modeled. The driver circuit current history is instead obtained experimentally and approximated as linear segments, in this case where residual magnetism is used as a latching force. The equations are solved using modified 4th order Runge-Kutta procedures with variable time step.

Primary interest is in delivery; secondary interests in closing pressure, needle lift, injection delay, injection duration, nozzle flow discharge coefficient, pressure histories (intensifier, accumulator, and sac), injection rate, and jet velocity. Figures 12 through 20 contain the results of these calculations from the simulation.

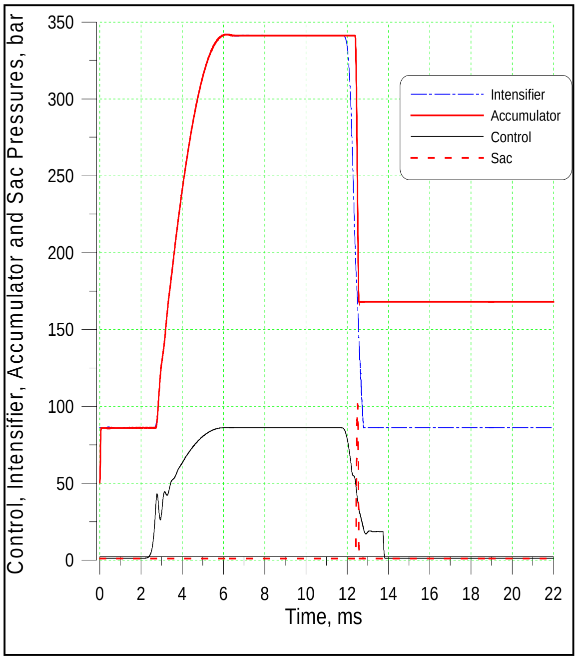


Figure 12. Pressure Histories versus Time

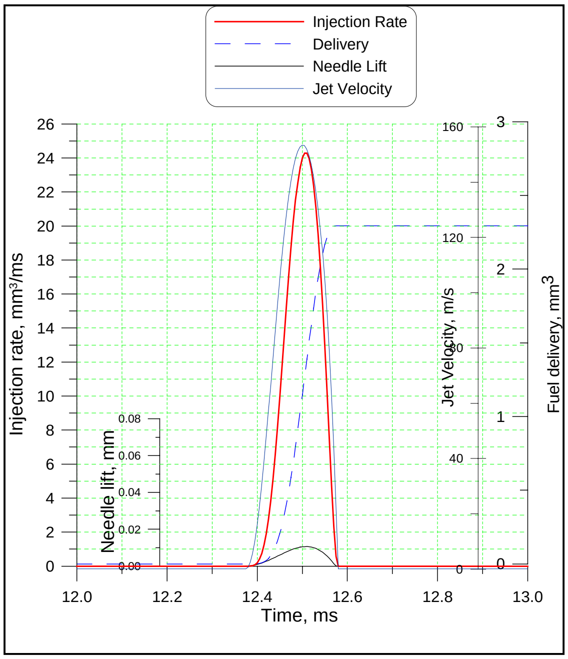


Figure 13. Injection Rate, Delivery, Needle Lift & Jet Velocity versus Time

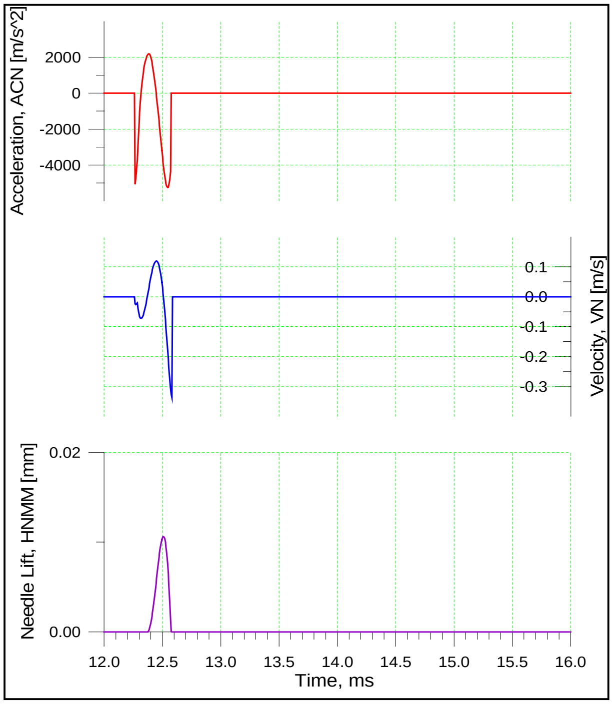


Figure 14. Needle Dynamics

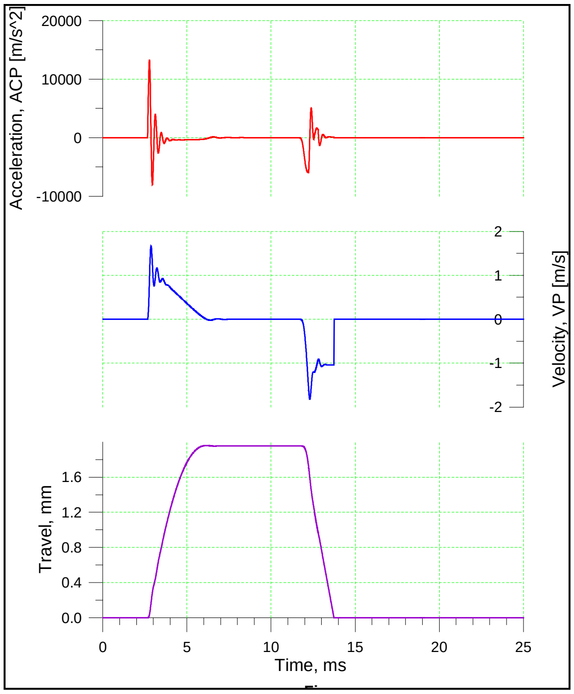


Figure 15. Intensifier Piston/Plunger Dynamics

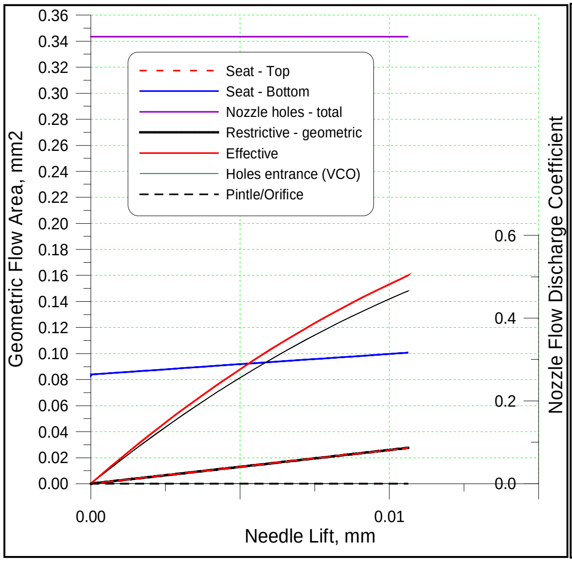


Figure 16. Flow Coefficients

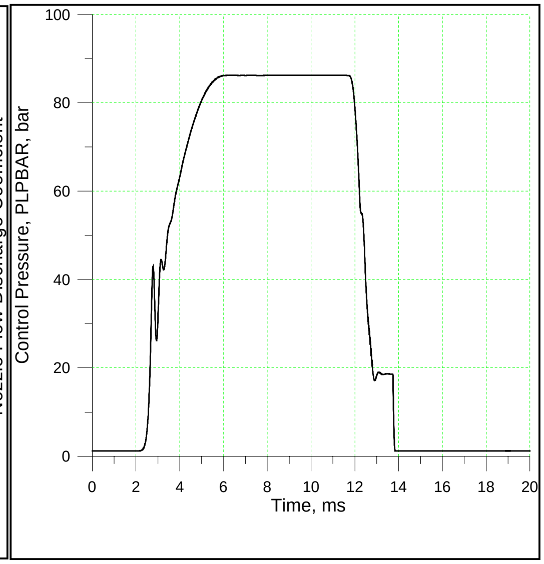


Figure 17. Control Pressure History

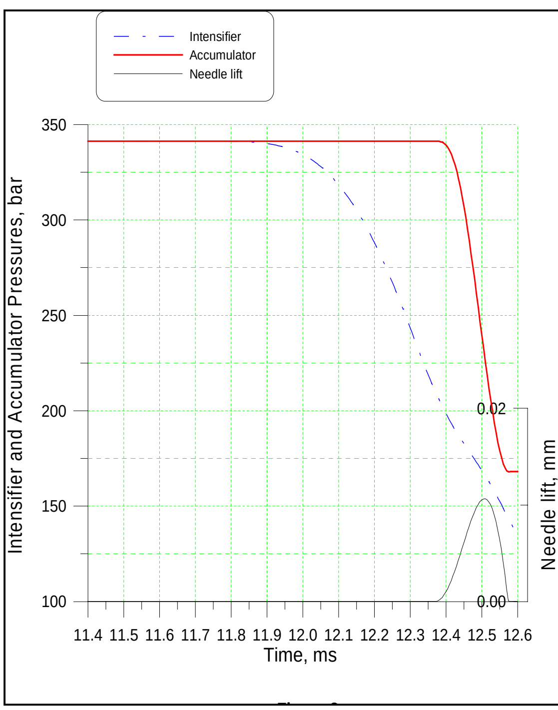


Figure 18. Needle Lift, Intensifier & Accumulator Pressure History

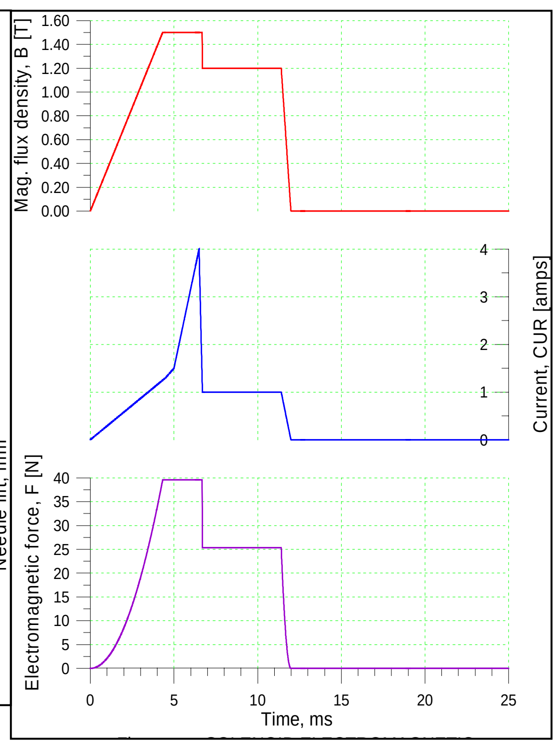


Figure 19. Solenoid Electromagnetic Properties

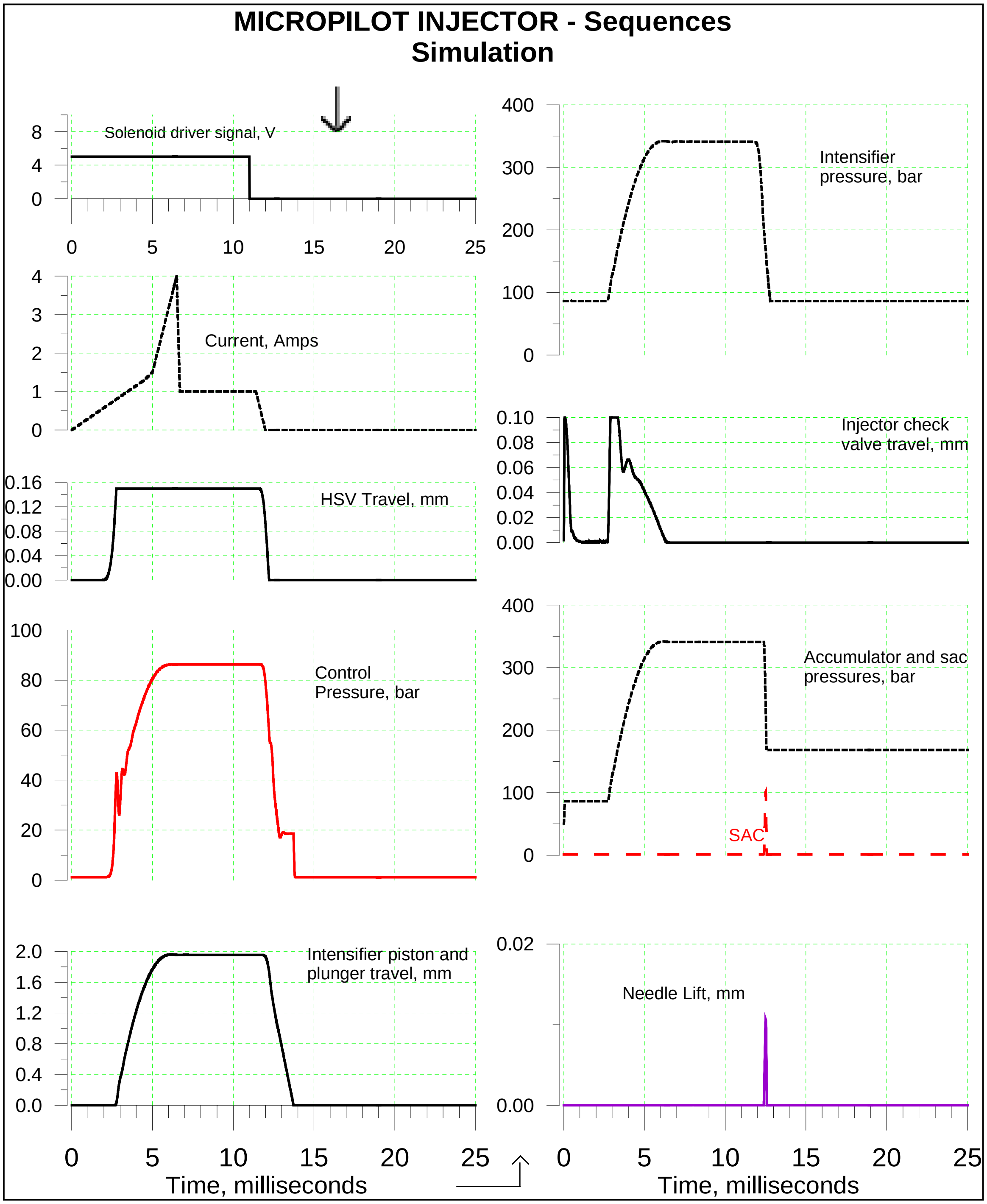
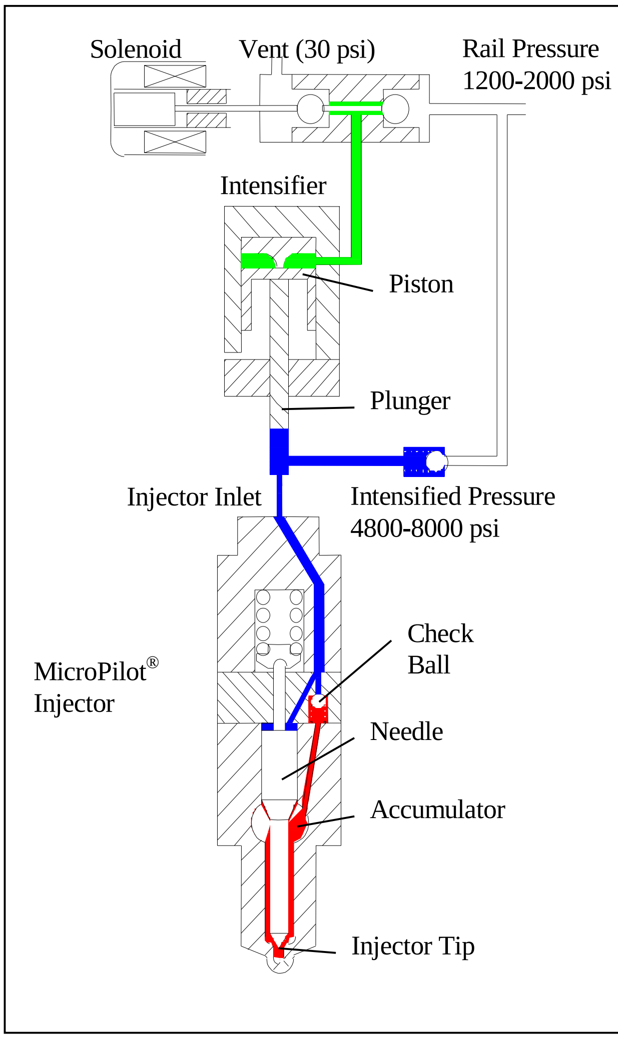


Figure 20. MicroPilot® Injection Process from Solenoid Driver Signal to Needle Lift These graphs describe the steps to injector fuel through the MicroPilot® injector.

Closing pressure, as measured in physical testing, is adequately high enough (3000 psi) to avoid possibility of needle being re-opened by combustion event. Injection delay and duration, calculated in simulation and measured in calibration are appropriate for injection. Accumulator pressure in simulation does not precisely match physical calibration; simulation indicates a lower closing pressure. Regardless of indicated closing pressures, both pressure histories indicate no pre-mature needle closing. The actual closing pressure history does indicate slow leakage after closing, but this is probably leakage past the check ball, not past the needle.

4.5. One Percent MicroPilot® Injectors

MicroPilot® injectors are standard diesel pencil type injectors that have been modified to work with a peak injection pressure of 4,800-8,000 psig and injection duration of less than 1 millisecond. This results in an injector that operates in the range of 2.5~5.0mm³ per injection, or 1~2% of maximum fuel (Figures 21 and 22). The one percent MicroPilot® injectors have four equally spaced 0.18 mm diameter holes in the tip.



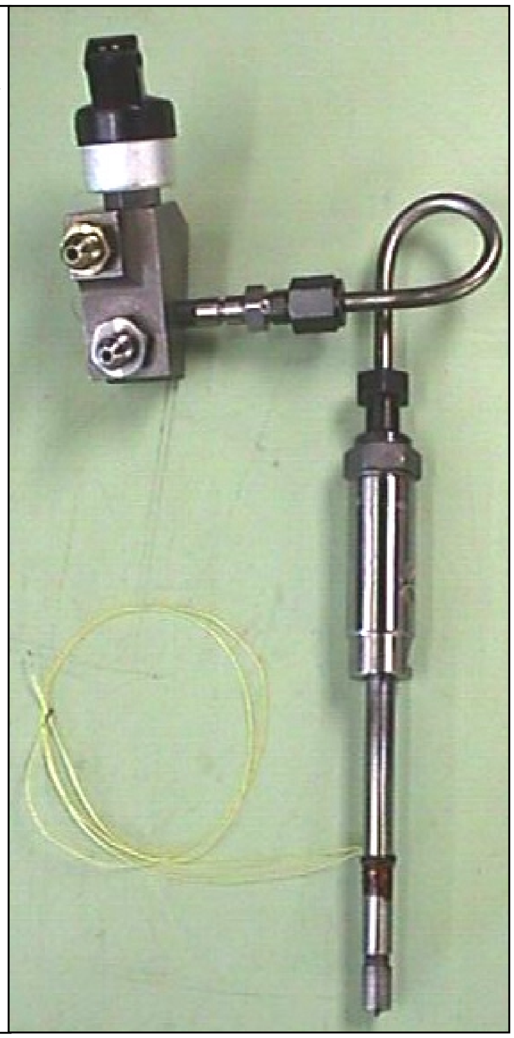


Figure 21. Schematic of MicroPilot® Injector and Intensifier

Figure 22. Photograph of MicroPilot® Injector and Intensifier

4.6. Lube Oil

4.6.1. Fuel Supply System

A new fuel supply system was fabricated to run lube oil to the pilot fuel rails. The new system consisted of a fuel tank, a low pressure pump, a fuel flow measurement turbine meter, a high pressure pump and an electronic pressure regulator. This new fuel system was fabricated to prevent contamination of fuels and facilitate easier swapping of fuels. Specially formulated SAE 40W ash-less lube oil was used for testing. Ash-less lube oil was used to reduce particles that could plug injector nozzles.

4.6.2. Two Percent Lube Oil Pilot Results

The engine was initially tested on two percent diesel for Task two.1 and therefore the first testing with lube oil was done with the same two percent injectors at two percent (~5mm^3). The testing reported here was accomplished with the two percent MicroPilot® injectors operating with lube oil.

The engine was able to start on room temperature lube oil, but the startup did take slightly longer than on diesel, and was characterized by audible late ignition and misfire. Startup refers to the period of cranking when engine speed is less than 350 rpm.

Additionally, during the warm-up phase, the engine exhibited poor combustion quality, late ignition and misfire (determined by in-cylinder pressure monitoring). Warm-up on lube oil was characterized by high fuel consumption, uneven exhaust temperatures and cylinder misfire. Warm-up refers to the period of time that the engine can be run low speed, but has low exhaust gas temperatures (less than 200°F), low coolant temperature (less than 150°F), and will not run at 1800 rpm or accept load. Once the engine is warmed up, it behaves very similar to diesel. The testing was accomplished by warming up the engine on diesel, before switching to lube oil, to facilitate easier testing and avoid dangerous unburned natural gas build-ups in the exhaust system.

AVL cylinder pressure monitoring was used to observe combustion pressure and derive combustion quality results. Combustion delay, combustion duration, IMEP, and peak pressure values measured with lube oil pilot were equivalent to values measured with diesel pilot (Figures 23, 24, 25, and 26). The consistency of these cylinder pressure derived indexes testifies that lube oil operates almost identically to diesel as a MicroPilot® fuel. Additionally, thermal efficiency and BSNOx values with lube oil are very similar to the values with diesel (Figures 27 and 28).

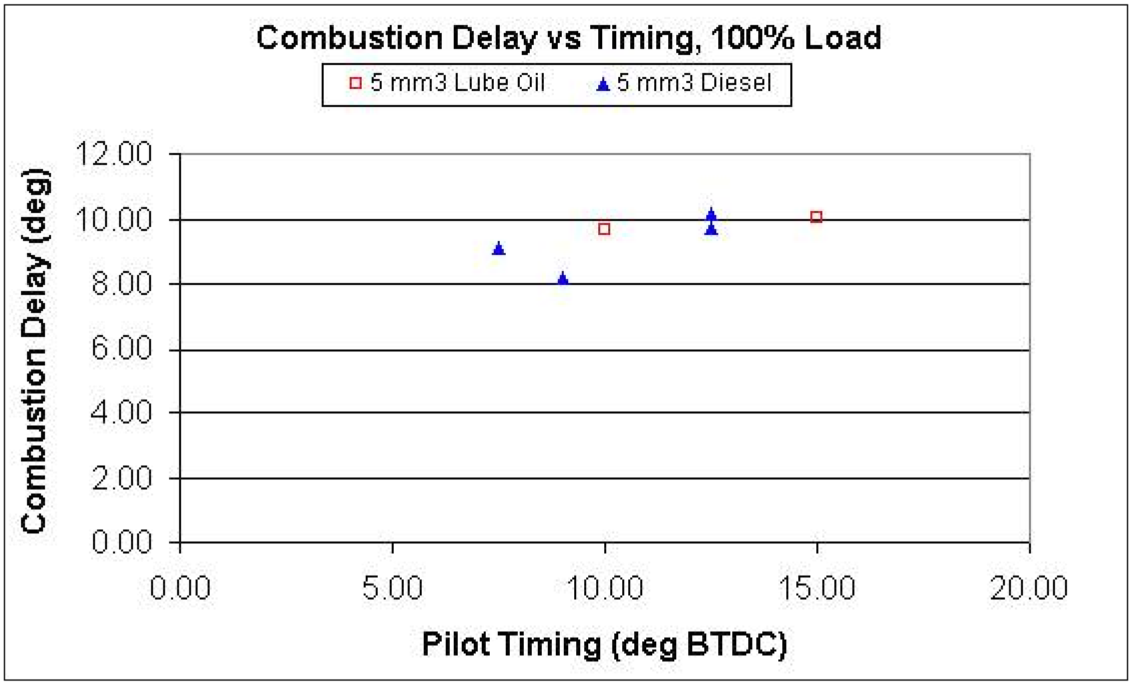


Figure 23. Combustion Delay versus Timing at 100% Load, (lambda 2.0)

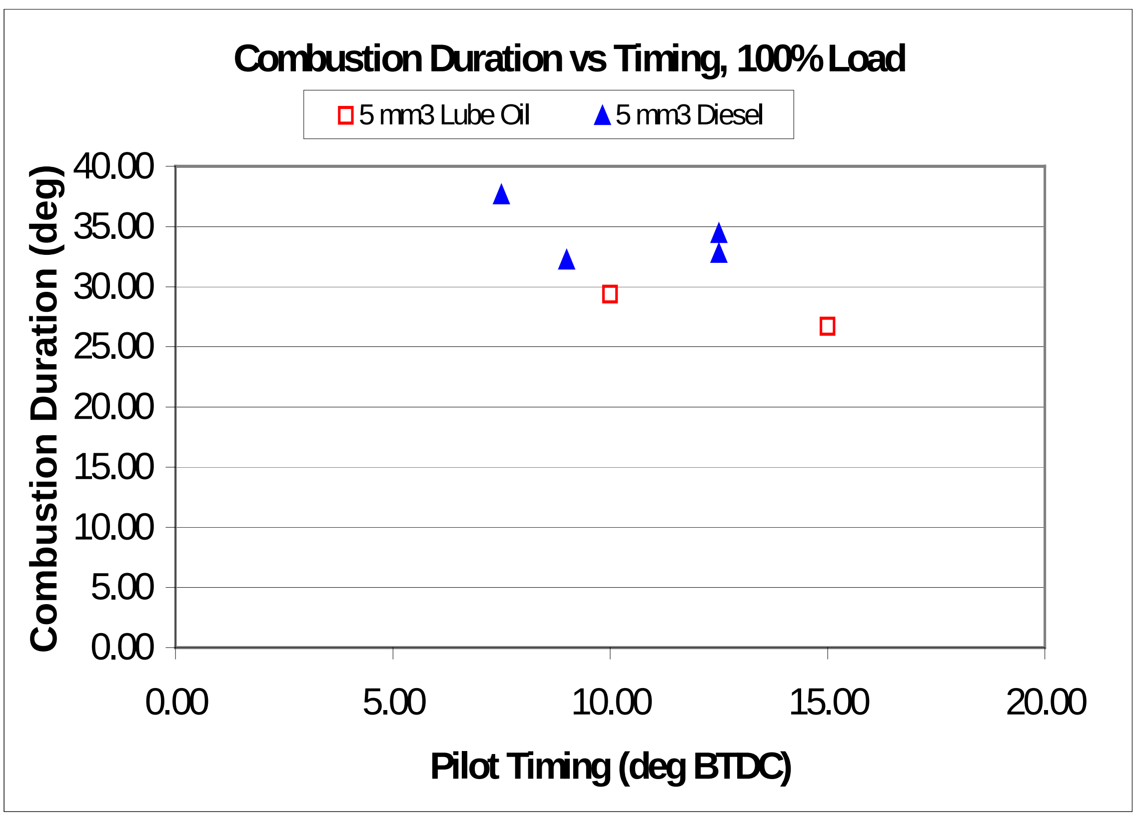


Figure 24. Combustion Duration versus Timing at 100% Load, (lambda 2.0)

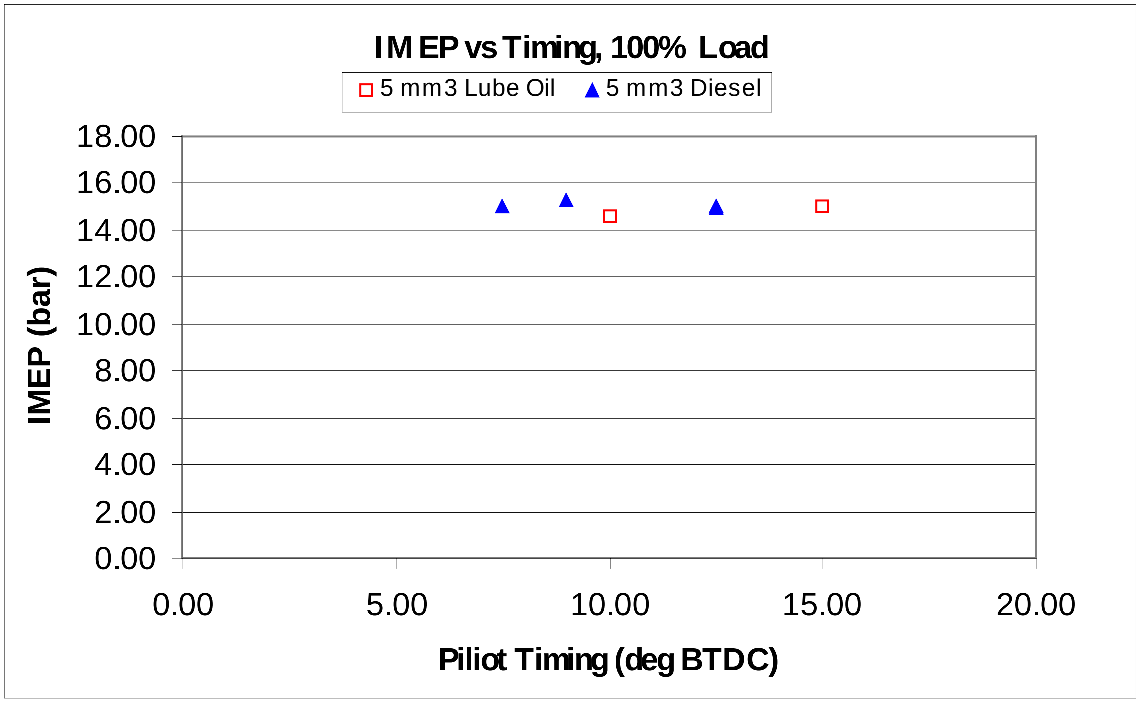


Figure 25. IMEP versus Timing at 100% Load, (lambda 2.0)

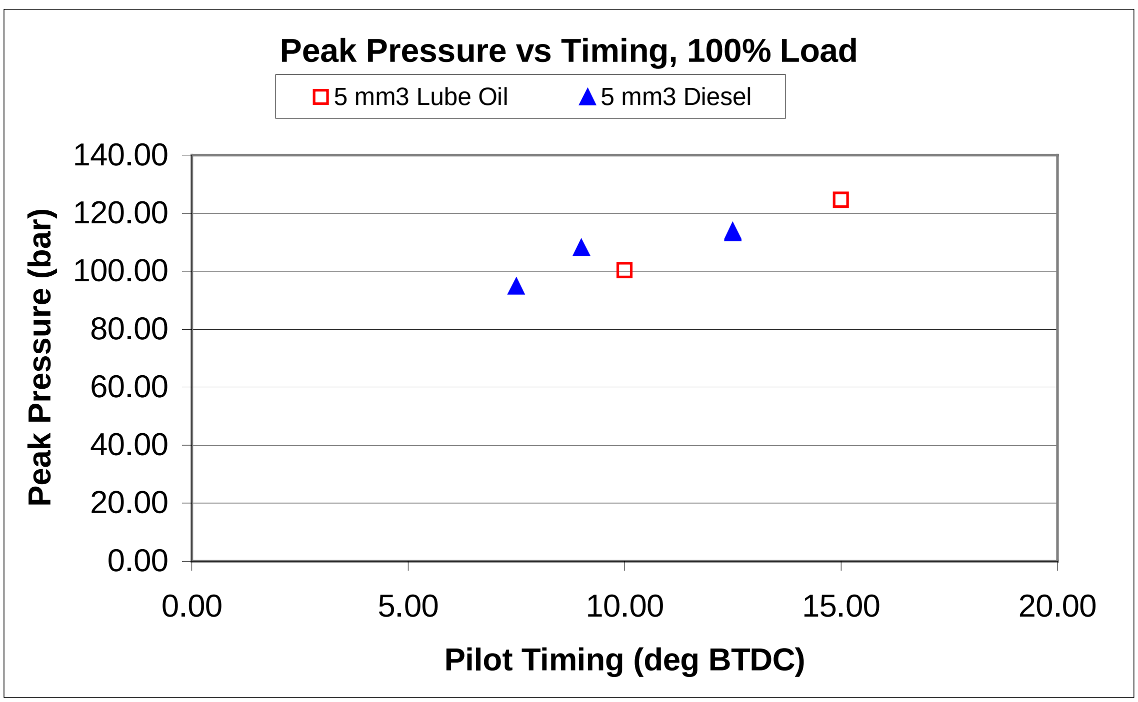


Figure 26. Peak Pressure versus timing at 100% Load, (lambda 2.0)

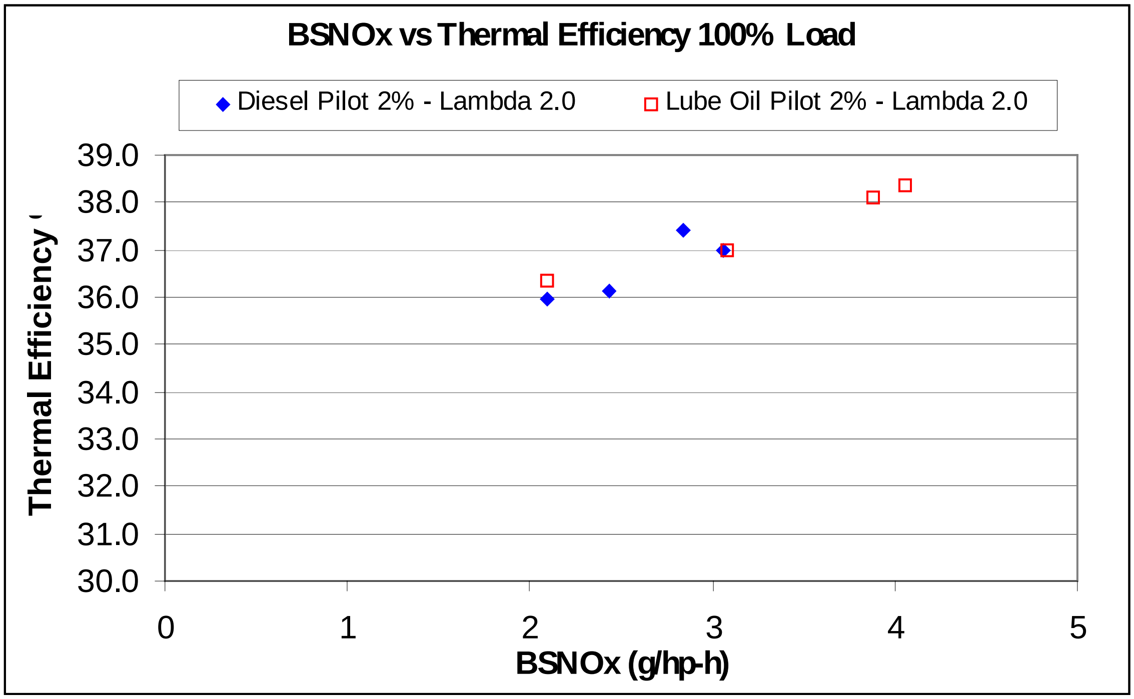


Figure 27. BSNOx versus Thermal Efficiency 100% Load

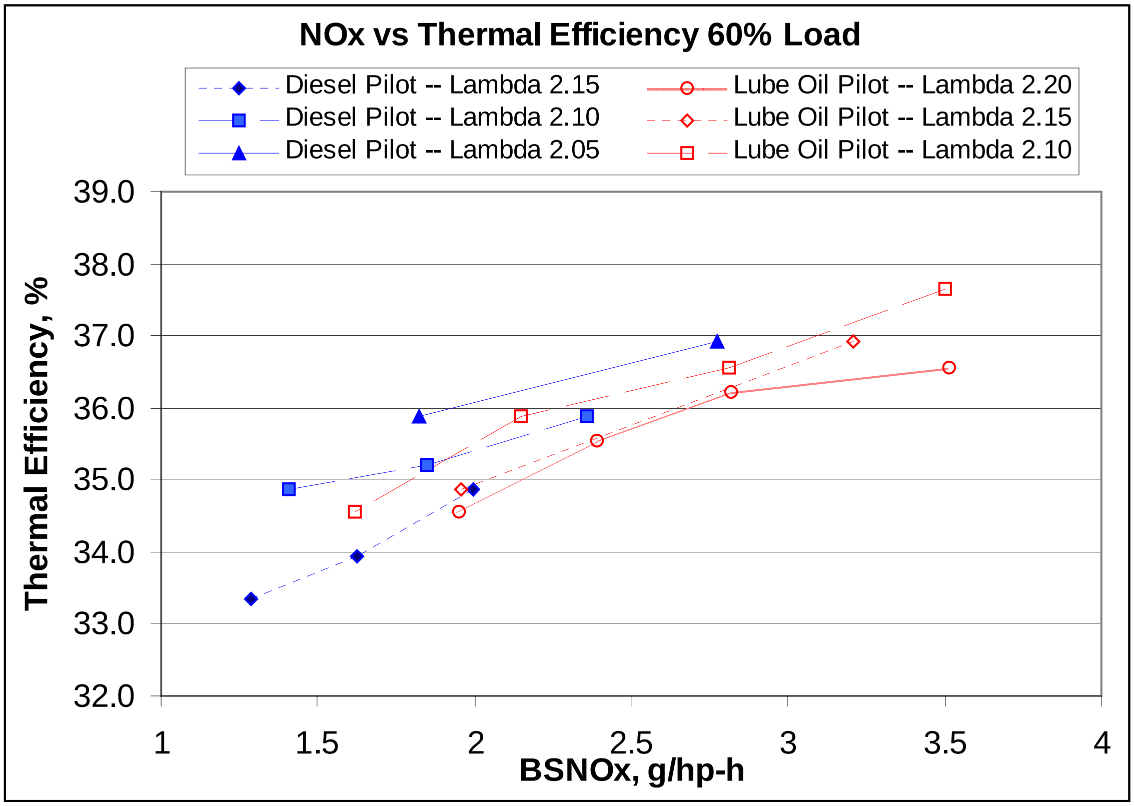


Figure 28. BSNOx versus Thermal Efficiency at 60% Load

4.6.3. Lube Oil Discussion

Operation on one percent and two percent lube oil was demonstrated. Practical application considerations for commercialization have also become evident. Solutions to these issues will determine the commercial feasibility of the lube oil pilot. Startup and warm-up with lube oil is a problem with lube oil as a pilot fuel. The problem with cold lube oil in a cold engine is the poor spray quality (caused by increased viscosity) observed in a previous report (Task two.one Report). This problem goes away when the engine is heated, because the lube oil is hot by the time it reaches the injectors and spray quality is adequate. Once the lube oil is heated, it yields the same NOx and thermal efficiency as the diesel pilot.

The specially formulated SAE 40W ashless lube oil was used because previous lube oil pilot testing showed that ash and long chain polymers can cause soot build-up on the injector nozzles. Using this specially formulated lube oil raises a number of concerns, including the fact that it is currently not approved for engine crankcase use. The process for approval requires considerable testing and time. Additionally, if crankcase lube oil is used, there are issues involving getting the oil to the injection system and dealing with the contaminates commonly found in used crankcase oil.

4.6.4. Calibration and Installation

Modified injectors (one percent) were installed on the 3406 genset and software was adjusted accordingly (calibration changes only) to accommodate new injectors. A new fuel supply module was connected to accurately measure diesel fuel consumption.

Initial testing at one percent load (on diesel and lube oil) indicated problems with the one percent injectors, including misfire at lower pilot quantities and audible engine knock. The remainder of testing with the one percent injectors was done at 60 percent load to reduce the possibility of damaging knock. Even at 60 percent load, advancing timing (with one percent injectors) can produce audible knock, therefore the engine was run as lean as possible (λ>two.0). It is important to note that the two percent injectors do not cause knock at 60 percent load, regardless of timing. Cylinder pressure monitoring was used to detect knock.

The one percent injectors were initially calibrated on a test stand that determines delivery from an average of one injection event. This information was then input to the electronic controller, which then attempted to regulate rail pressure to maintain the desired delivery quantity. The electronic controller does not measure fuel quantity; it regulates rail pressure to obtain a desired quantity. To validate the injector calibration, actual fuel quantity was measured with a rotameter while the engine was running. The flow measurement indicated correlation between measured and desired fuel consumption.

Minimum pilot quantity was determined by reducing pilot delivery until engine exhibited misfire (as indicated by low exhaust gas temperature), and then increased back to a point where the engine is able to run without misfire.

4.6.5. Engine Test Results of One Percent Lube Oil Injectors

During the test program, a decision was made to experiment with various actual fuel deliveries, regardless of the one percent or two percent injector design goals. Therefore, for the remainder of this report, the terms one percent and two percent will refer to the injector design configuration rather than actual fuel delivery. The actual volumetric fuel delivery will be presented with the test description.

The one percent injector started and ran at 5.0mm^3 and 2.9mm^3 or two percent and 1.2 percent of total fuel on lube oil, respectively (Table 4). The engine did not run properly when pilot quantity was reduced to 2.5mm^3 (1.0 percent), and exhibited extremely high hydrocarbons and misfire (with or without load), the engine was therefore run at 2.9 mm^3 for the minimum pilot quantity. When run at 60 percent load and 5.0mm^3 of pilot, the engine (with one percent injectors) required approximately one0 degrees of additional injection timing advance, compared to the two percent injectors, to achieve the same levels of NOx and thermal efficiency.

Table 4. One Percent Injector Characteristics

Injectors	1% Injector	1% Injector
Quantity Injected mm^3	5.0	2.9
Peak Injection Pressure, psi	9000	7000
Pilot Timing to achieve 2.0 g/hp-h NOx at λ > 2.1, deg BTDC	26	~22[1]
Thermal Efficiency at 2.0g/hp-h NOx & λ > 2.1, %	35.5	33[1]
NOx at 34% Thermal Efficiency & λ > 2.1, g/hp-h	1.6	2.9

The engine did not achieve similar NOx and thermal efficiency numbers (with equivalent lambda) while running at 2.9mm^3 (1.2%). For equivalent timing and thermal efficiency, the engine produced 40-60 percent more NOx with the one percent Injectors running at 2.9mm^3 than running the same injectors (or the two percent injectors) at 5.0 mm^3 (Figure 29).

Cylinder pressure analysis (Figure 30) gives additional insight to the previously noted data. Cylinder pressure data shows higher peak pressure and IMEP (in cylinder #1, constant timing & lambda) when running the one percent injector on 2.9 mm^3 than on 5.0 mm^3. Table 5 shows a comparison of the results for the two pilot quantities.

[1] Lowest NOx of 2.4 (g/hp-h) was achieved at 24 degrees; 2.0 (g/hp-h) at 22 degrees is assumed by linear extrapolation.

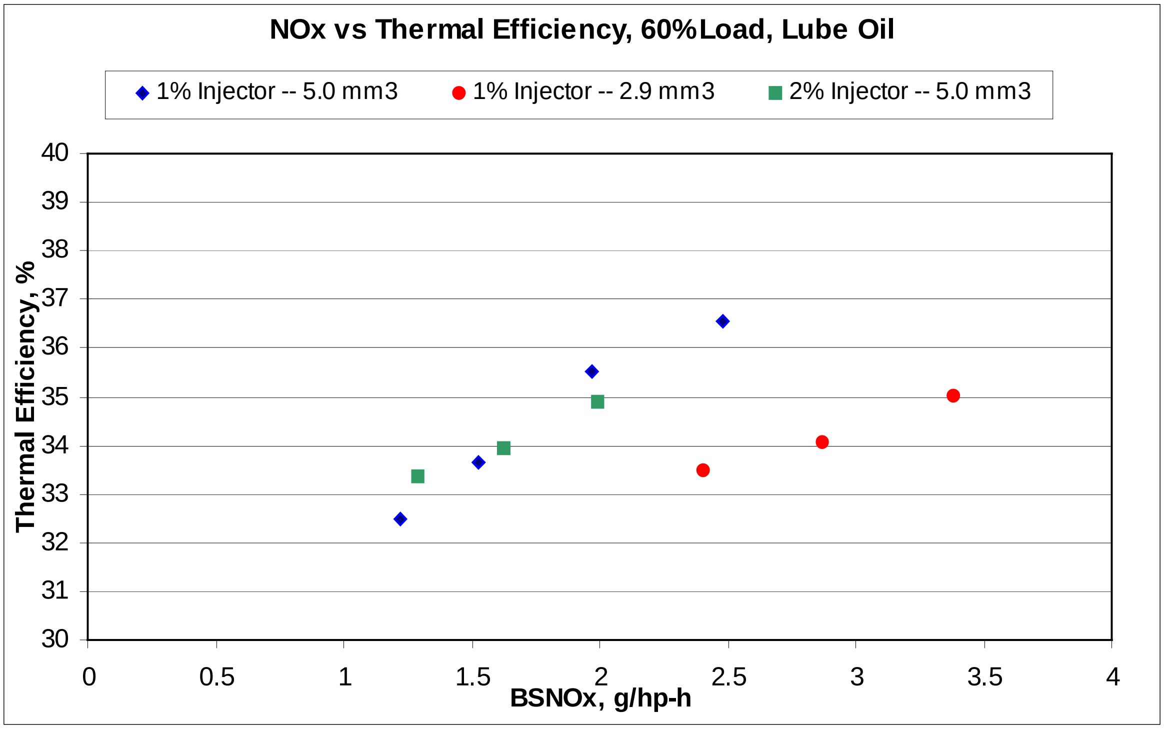


Figure 29. NOx versus Thermal Efficiency
This graph shows NOx versus Thermal Efficiency referenced by pilot injector and delivery. The 1% injector running at 2.9 mm^3 shows considerably higher NOx than the injectors running at 5.0 mm^3.

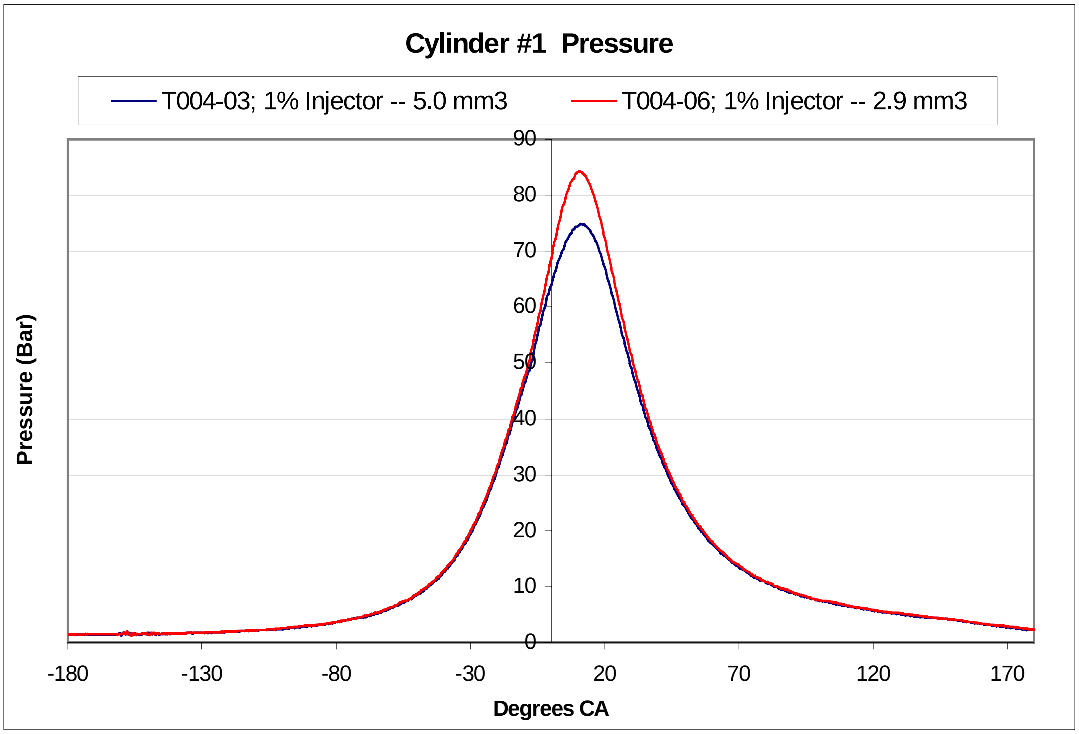


Figure 30. Cylinder Pressure versus Degrees Crank Angle Lube oil @ 60% load. Blue line is 1% injector at 5.0 mm^3 per injection and red line is 1% inj at 2.9mm^3

Table 5. One Percent Injector, 5.0 mm^3 versus 2.9 mm^3

Test Point	T004-03	T004-06
Quantity Injected	5.0 mm^3	2.9 mm^3
Speed	1800 RPM	1800 RPM
Load	60% (154kW)	60% (154kW)
Pilot Timing BTDC	26°	26°
Lambda Measured	2.1	2.1
Peak Cylinder Pressure	75 bar	84 bar
Location of Peak Cylinder Pressure degrees ATDC	11.00°	10.77°
IMEP	10.5 bar	11.4 bar
BSNOx	2.0 g/hp-h	2.9 g/hp-h
Thermal Efficiency	35.5 %	34.1 %
Max Rate of Pressure Rise	2.54 bar/msec	2.95 bar/msec
Ignition Delay	24.0°	23.0°

Higher peak pressures and IMEP (with the 2.9mm^3 delivery) are accompanied by higher BSNOx. However, the thermal efficiency is lower with the smaller delivery (high peak pressures, IMEP, etc).

4.6.6. Comparison of Two Percent Injector versus One Percent Injector

The one percent injector (at 5.0 mm^3) performs similar in BSNOx versus Thermal Efficiency tradeoff, to the two percent injector (at 5.0 mm^3) (Table 6). Aside from differences in injection parameters (duration, pressure, etc) and hence, a difference in ignition delay, the 3406 with the one percent injector (at 5.0 mm^3) performs similar to the 3406 with the two percent injector (at 5.0 mm^3).

Table 6. One Percent Injector versus Two Percent Injector Comparison

Injectors	1% Injector	2% Injector
Quantity Injected	5.0 mm^3	5.0 mm^3
Peak Injection Pressure	9000	5400
Pilot Timing to achieve 2.0 g/hp-h NOx at $\lambda > 2.1$	26°	17°[2]
Thermal Efficiency at 2.0g/hp-h NOx & $\lambda > 2.1$	35.5%	35 %
NOx at 34% Thermal Efficiency & $\lambda > 2.1$	1.6 g/hp-h	1.6 g/hp-h
Ignition Delay @ 2.0 g/hp-h NOx & $\lambda > 2.1$	24°	18°
Peak Cylinder Pressure @ 2.0 g/hp-h NOx & $\lambda > 2.1$	75 bar	93 bar
IMEP @ 2.0 g/hp-h NOx & $\lambda > 2.1$	10.55 bar	13.46 bar
Max Rate of Pressure Rise @ 2.0 g/hp-h NOx & $\lambda > 2.1$	2.54	3.12
Nozzle Configuration	4 x .18mm	4 x .15mm

4.6.7. Analysis One Percent Lube Oil Pilot

While the one percent Injector did create results similar to the two percent injector (at 5.0 mm^3), it is less than adequate at 2.9 mm^3. The higher IMEP observed from cylinder #1 and lower thermal efficiency indicates that there is a cylinder to cylinder consistency problem. In order for the IMEP (of cylinder #1) to have increased while BMEP stays the same, the IMEP from another cylinder (or more) must have decreased.

4.7. Warm-up

Early tests with the MicroPilot® 3406 demonstrated poor operating qualities during cold (ambient temp 60°F, 16°C) startup. The engine exhibited poor combustion quality from continuous misfire through high fuel requirements, high exhaust gas hydrocarbons (10000+ ppm) and unsteady engine speed. This poor warm-up quality only exists when the engine is started cold and disappears as soon as engine coolant temperature (ECT) reaches 50°C.

Three solutions were implemented to the startup / warm-up problem. First, the engine was run to 1200 rpm after cranking for warm-up. Originally the engine warmed up at

[2] NOx = 2.0 g / hp-h & Lambda >2.1, data is taken from test point T003-02

600 rpm, but it was discovered that 1200 rpm warm-up was much quicker than 600 rpm. Second, an electric jacket water heater was installed in the cooling system to raise the coolant temperature to 40 °C before the engine is started. Third, the engine was started and warmed up in the skip-fire operating mode. Running in skip fire (2-3 cylinder) allows for higher BMEP per firing cylinder and hence fewer occurrences of misfire and quicker warm-up.

Figures 31, 32, and 33 demonstrate the advantages of the block heater and skip fire. With the block heater and skip fire strategy, warm-up time was decreased from 15 minutes to 4 minutes.

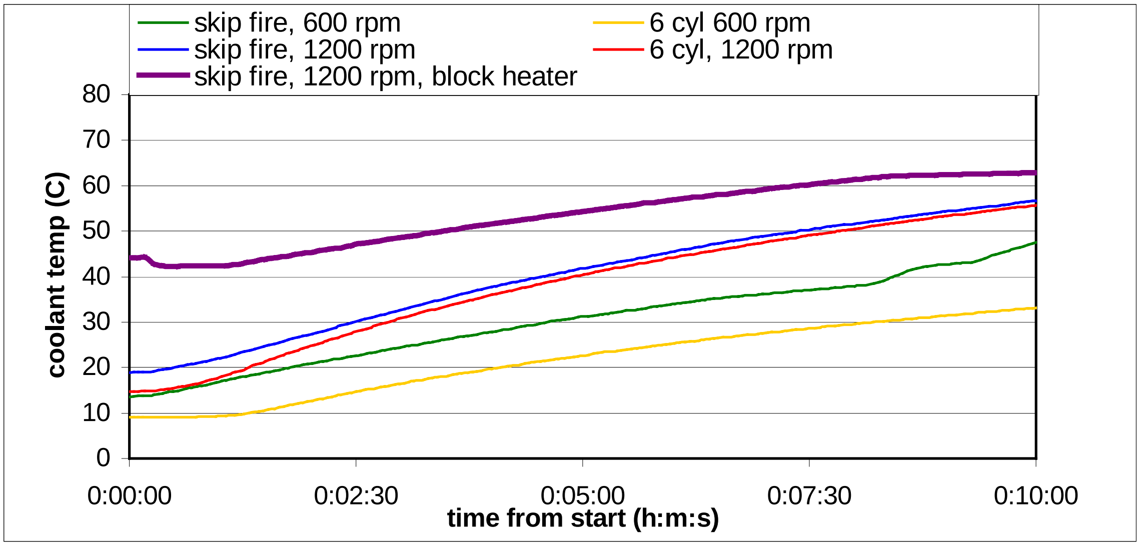


Figure 31. Coolant Temperature versus Time from Engine Start
The effect of the block heater and skip fire can be clearly seen.

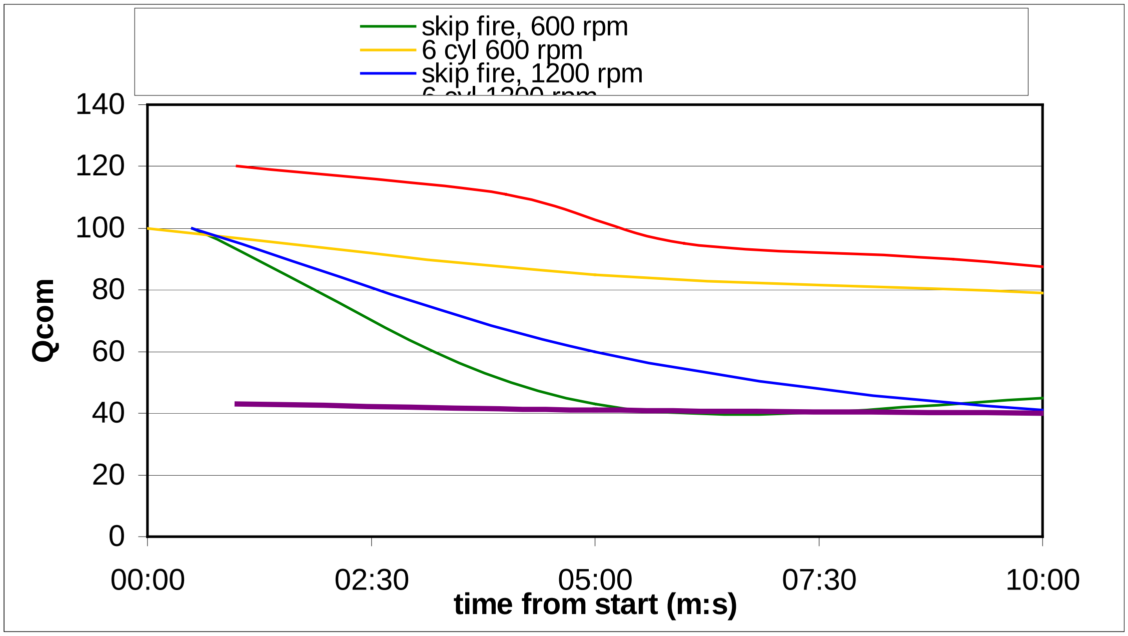


Figure 32. Fuel Commanded (Qcom) versus Time from Start
Skip fire with block heater uses the least amount of fuel during startup.

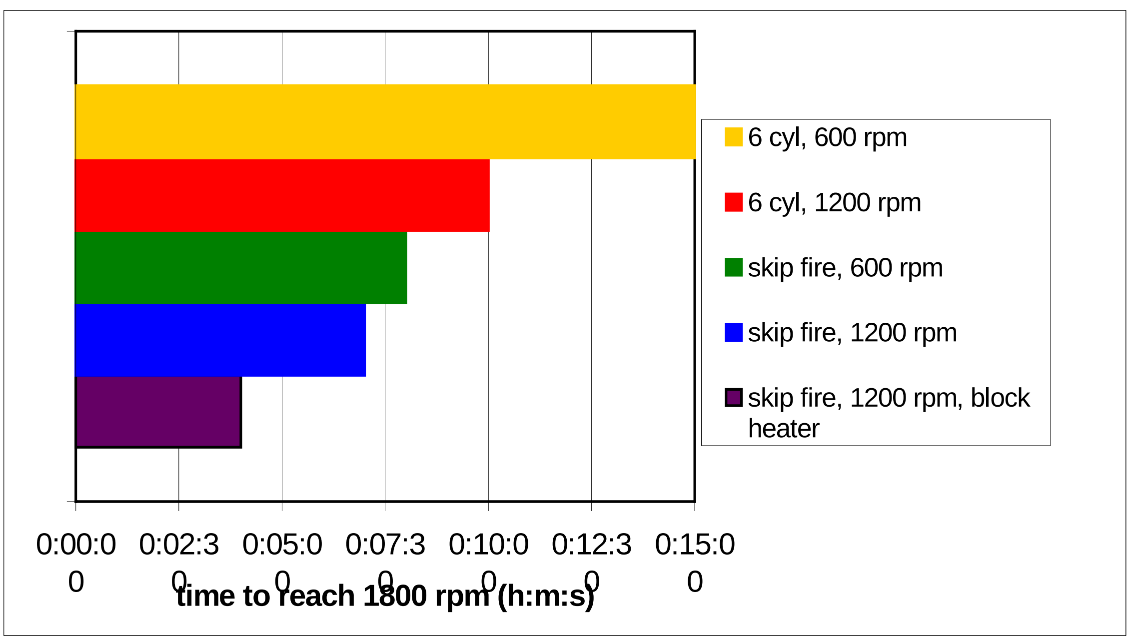


Figure 33. Time for engine to Crank, Start, Warm-Up at 1200 rpm, Accelerate to 1800 rpm, and Accept 50% Load at 25°C Ambient Starting Temperature

4.8. Problems

4.8.1. Research and Development Issues

The primary research or technical problems with the one percent MicroPilot®development were cold lube oil starting, injector soot buildup, and cylinder-to-cylinder spray quality. The one percent MicroPilot® and two percent MicroPilot® engines exhibited poor combustion quality and misfire during starting and warmup (ACT < 150 F) while running on lube oil. This poor starting can be prevented by pre-heating the lube oil, but is still a major concern for genset applications. Soot buildup on the injector nozzles was observed with standard Caterpillar lube oil, but was not as prevalent with the constant weight ashless lube oil specially formulated for this application. Cylinder-to-cylinder spray quality is also a major concern with the one percent MicroPilot® injectors. Spray quality variations result from sensitivity to component and assembly tolerance variations for the small fuel delivery required. If one cylinder has a higher energy spray, it ignites the gas mixture sooner and essentially causes that one cylinder to behave as if it is advanced and has high NOx and high thermal efficiency. Other cylinders with poor spray energy (and quality) will have low NOx and low thermal efficiency. This unbalance will cause a poor running engine and inadequate NOx/Thermal efficiency tradeoff.

4.8.2. Product Commercialization Issues

The major product commercialization issues with the one percent Lube Oil MicroPilot® are manufacturing the one percent Injector and certification of ashless lube oil. To reduce injection quantity from two percent (5 mm^3) to 1 percent (2.5 mm^3), considerable changes were required to the injector, including hard chrome plating the injector needle. This process is expensive and not very precise and results in large injector to injector variability. The issue of using ashless lube oil is necessitated by soot buildup on the injector nozzle. However, the lube oil was specially formulated for this use and would need to be certified and accepted before it could be used on any engine. Also, using crankcase lube oil requires considerable effort on the delivery to the injection system and on filtering the contaminates because the oil would be dirty from engine use.

4.9. Conclusions

- Operation of the 3406 genset on 1.2 percent lube oil pilot has been demonstrated.
- The 3406 one percent Lube Oil MicroPilot® genset did not meet the project goal of 1.5 g/hp-hr NOx at 38 percent or greater thermal efficiency.
- The one percent MicroPilot® system using the modified standard Caterpillar diesel injectors is not adequate for dual fuel pilot ignition.

4.10. Recommendations For Future Research and Development

- Design an optimized one pwercent MicroPilot® injector and retest lube oil and diesel NOx/thermal efficiency tradeoff.
- Certify (and possibly re-formulate) ashless lube oil for engine crankcase use.

5.0 Task Report 2.3: Development of a 2% MicroPilot® Fuel Injection System for the CAT 3412 Generator Set Engine

5.1. Introduction

This report describes BKM's efforts to design, develop and demonstrate a CAT 3412 Generator Set with the two percent MicroPilot® Fuel Injection system.

5.1.1. Task Objectives

The objective of this task was to purchase and modify a CAT 3412 Diesel Genset to operate with a MicroPilot® Fuel Injection System.

5.2. Task 2.3 Work Plan

a) Purchase CAT 3412 Genset for field service.

b) Fabricate additional MicroPilot® injectors and design the other components required for the CAT 3412 Genset, install MicroPilot® fuel system.

c) Expand control software for 12-cylinder operation.

d) Install Genset in CAP's test cell area.

e) Initial engine testing and troubleshooting.

5.3. Purchase CAT 3412 Genset for Field Service

BKM purchased a CAT 3412 genset (recondition) from Power Systems Associates in Los Angles California. The genset was delivered to BKM (Figures 34 and 35).

Figure 34. Front-End View of the CAT 4312 Genset

Figure 35. Right Side of the Engine

5.4. Fabricate Additional MicroPilot® Diesel Fuel Injectors and Design the Other Components Required for the CAT 3412 Genset, Install MicroPilot® Fuel System

New and additional parts were designed, fabricated and bench tested in order to adapt the engine to a MicroPilot® fuel system.

5.4.1. Two Percent MicroPilot® Diesel Fuel Injectors (12)

The injectors are modified from stock CAT diesel injector bodies. Each injector must be mated with a special nozzle that has been hand crafted by BKM personnel. Figure 36 shows a photo of one of the 12 MicroPilot® diesel fuel injectors. The purpose of these nozzles is to supply the pilot fuel required to ignite the natural gas in the engine combustion chamber. These particular nozzles supplied a maximum of two percent fuel, therefore, the engine would be unable to start or run as a diesel engine.

Figure 36. One of the 12 MicroPilot® Fuel Injector Nozzles fabricated for the 3412 Engine

5.4.2. Two Percent MicroPilot® Diesel Fuel Injector Intensifiers (12)

The injector intensifiers (Figure 37) are pre-production components of the pilot fuel system. Each intensifier must be hand built and mated to the injection nozzle and then fine-tuned to optimize the unit's performance. Twelve intensifiers are required for the 3412 engine. The function of the intensifier is to take the common rail pressure and intensify (increase) the fuel pressure to a predetermined value during the fill cycle. At the proper moment, the ECU sends a command signal to the appropriate injector's solenoid valve and energizes (opens) the solenoid that causes the intensifier to vent and the injection event to take place.

Figure 37. Intensifier portion of the Pilot Diesel Fuel Injection System

5.4.3. Common Rail Fuel System for a MicroPilot® Diesel Fuel System

The common rail fuel system incorporates a high-pressure pump that is shown in Figure 38. The pump is a 5 piston positive displacement pump that provides high pressure (1,500 PSI) diesel fuel to the common rail fuel supply system, which in turns provides fuel to each of the 12 MicroPilot® Fuel Injectors. The common rail system also includes an Electronic Fuel Pressure Regulator to maintain the common rail pressure as commanded by the Engine Control Unit. As well as the major components, there is also the necessary plumbing, valves, instrumentation and filters found in any liquid fuel system.

Figure 38. Fuel Pump Developed for the Common Rail Fuel System used with the MicroPilot® Fuel Injection System

5.4.4. Natural Gas Fuel Injection System

The Natural Gas Fuel Injection System for this engine is a spin off from a CAP commercially available system for Dual-Fuel™ truck engines. However, the multi-point injection system (individual cylinder gas injectors are shown in Figure 39) requires that the cylinder head be removed from the engine. Once the heads (2) are removed they are reworked to enable the installation of gas supply tubes for the injection of the natural gas upstream of the engines intake valves. The CAT 3412, 12-cylinder engine requires 24 natural gas injectors (two per cylinder) in order to flow the amount of natural gas needed at full power.

**Figure 39. Natural Gas Fuel Injector Blocks for 2 Cylinders
Each with the 2 injectors and piping needed to connect the system.
Sufficient parts were manufactured to supply fuel for all 12 cylinders**

Another option, the single point gas injection system was reviewed and considered as a lower cost alternative to the multi point system. The difference between multi point and single point is primarily the way the gas is introduced into the engine's combustion air system. Figure 40 shows the single point gas injector developed for this project. This component may offer advantages over the multi point system because the installation is far less complex and allows a lower natural gas supply pressure to be used. However, it may not be able to deliver fuel to the engine cylinders as efficiently as the multi point system, therefore engine-out exhaust emissions maybe higher.

Figure 40. Single Point Fuel Injector

Other common components required for a gas system include a Primary Fuel Filter (Figure 41), an Electronic Shut Off Valve, the Electronic Fuel Pressure Regulator (Figure 42) and the necessary plumbing to route the gas as necessary. In addition, sensors and other instrumentation for use by the Engine Control Unit were developed and used on the 3406 and were evaluated for use on the 3412. Figure 43 shows the speed pick-up component mounted in the front pulley area of the engine. The function of this device is to precisely monitor engine RPM and update the ECU with speed information.

Figure 41. Primary Natural Gas Fuel Filter
This filter is the first of two used in the system in order to prevent particulate matter from entering the gas fuel system from the gas supply.

Figure 42. Electronic Fuel Pressure Regulator (EPR)
The purpose of the EPR, developed for the pilot fuel injection system, is to regulate and maintain the fuel pressure in the common rail as required by the ECU

Figure 43. Speed Pick-Up Component Mounted in the Front Pulley Area of the Engine

Additional Equipment and accessories to be developed for the 3412 genset included developing the hardware and software for the ECU and the wiring harness for both the diesel and gas systems.

Initial drawing packages were completed for the major components and assemblies that were designed for use on the 3412 engine. New parts were bench tested as appropriate. The Turbo Air Bypass (TAB) valves (Figure 44) were to be used on the engine. The function of the TAB valve is to provide electronic control of the boost pressure developed by the two turbochargers utilized on the 3412 CAT Diesel Genset.

Figure 44. One of Two Turbo Air Bypass (TAB) valves Destined to be used on the Engine

During the course of this tasks activity, numerous unforeseen complexities arose that resulted in additional areas of investigation. Some of these issues were due to the physical layout of the V-12 engine, relative to the inline 6-cylinder engine, and the considerable design challenges the V-12 engine presented. Numerous configuration meetings were held to analyze and consider the following:

- Engine control unit
- The need for two gas valves per cylinder
- Uneven firing order. It was determined that the 3412 engine is an uneven firing engine, whereas most 12-cylinder engines fire every 60°; the 3412 fires every 55° then 65°.
- Fumigation manifold
- Fuel pump plate
- Electronic Pressure Regulator Block
- Parts for air routing
- After cooler system

5.4.5. Expand Control Software for 12 Cylinder Operation

Based on lessons learned during the operation of the 3406 MicroPilot® Genset development and the configuration meetings, it was discovered that the major pending issue with the development of the MicroPilot® 3412 is the complexity of the controller.

The electronic control unit (ECU) for the 3412 needs to real-time (high speed) control 24 independent injector drivers (12 gas, 12 diesel), one turbo air bypass (TAB) output, and one electronic pressure regulator (EPR) output, a total of 26 high-speed outputs (HSO).

The ECU developed by BKM has been used primarily for 6 cylinder engines and has only 18 high-speed outputs. Several solutions for this problem have been proposed, from a complete redesign on the ECU to using two separate controllers to control one engine.

Complete redesign of the ECU to function with the 12-cylinder engine is outside the scope and budget of the project. Any creative solutions, such as using two ECUs for one engine, will lack the robustness of using one ECU and will have a whole new set of issues regarding communication between the two ECUs. It was determined that any attempt at an ECU for the 3412 MicroPilot® within the scope and budget of this project would be at best a prototype and not a production design.

At this point in the project, several factors (budget, business issues and market potential) contributed to the delay in pursuing this approach that eventually resulted in development not being pursued. Therefore, no significant software work was undertaken.

5.4.6. Install Genset in BKM's Test Cell Area

This Task was not initiated.

5.4.7. Initial Engine Testing and Trouble Shooting

This Task was not initiated.

5.4.8. Problems Encountered

This task was more complex and expensive than originally envisioned. The issues are the result from configuration differences unknown at the time of the proposal. Those major differences between the CAT 3406 and 3412 included:

- Intake air system
- Gas fuel application design requirements

When it became apparent that Task 2.3 would not be accomplished with the budgeted Commission funds, CAP was approached (by BKM, at that time) to discuss additional funding for the phase. CAP committed to funding the remaining the remaining work in Task 2.3, with the condition that the CNG system would be multi-port injection. This was a departure from earlier plan, to apply single point electronic injection of the natural gas. The original design decision for single point was based largely on the desire to avoid cylinder head removal and modification for the port injection of natural gas. Cylinder head removal was not required for the installation of a multi point, injection system on the 3406. In conjunction with their funding commitment, CAP re-directed the design criteria to port injection. CAP had determined that commonality of the configuration; control strategy, experience and product image with a remainder of the CAP product line has priority over concerns of cylinder head removal for retrofit. This plan was initiated, with no additional Commission funds.

A few months later, the Marketing group of CAP, after consultation with Caterpillar, Inc. determined that the CAT 3412 Genset that BKM was developing as a MicroPilot® Genset, was to be discontinued. In addition, the style of diesel fuel injector for which BKM had developed low fuel and delivery modifications for (MicroPilot® ignition) was being phased out of production.

CAP determined that although additional development of the CAT 3412 MicroPilot® engine would be valuable research for other (future) products, that the 3412 was no longer a good candidate for commercial introduction of the MicroPilot® system. Funding and work on this task was therefore stopped, pending further discussion with the Commission.

Several conversations and meetings were conducted between the Commission, GRI and CAP to discuss how to complete the program within the time constraints of the program. GRI and CAP proposed the further development of the 3406 MicroPilot® system, to include durability testing, in place of the 3412 engine. It was determined that the program could not be completed, as currently planned, or modified and completed, within the time constraints of the contract. Therefore, no additional work was performed, and the project was concluded.

6.0 Task Report 2.4: CAT 3412 Genset Engine MicroPilot® Durability Test

6.1. Task Objective

The goal of this task is to successfully demonstrate the durability of the low-emission, high-efficiency operation of the CAT 3412 engine genset using MicroPilot® injectors.

6.2. Test Plan

a) Validate engine emission and efficiency levels and software stability. Finalize software calibration.

b) Place CAT 3412 genset with the MicroPilot® system in a location for evaluation of durability.

6.3. Work Performed

Task 2.4 was not initiated. Task 2.4 start was dependent upon the successful completion of Task 2.3. Task 2.3 was terminated prior to completion, as described in the previous section.

7.0 Conclusions and Recommendations

7.1. Conclusions

1. The CAT 3406 two percent MicroPilot® genset engine survived the durability test while meeting the project objectives for pilot quantity, emissions and thermal efficiency.

   - The genset was optimized to run at the following conditions:
     - NOx < 2.0 g/hp-h
     - Thermal Efficiency > 38%
     - Pilot Quantity 5.0 mm3 (2.25%) diesel per injection.
     - 80 hrs at 60% load (154 kW)
     - 20 hrs at 100% load (265 kW)
   - Emissions and thermal efficiency goals were met through the following strategies:
     - Optimized gas lambda with TAB valve air/fuel ratio control.
     - Minimized pilot quantity through calibration and testing
     - Optimized pilot timing through testing and NOx/Thermal efficiency tradeoff.
   - The genset achieved the goal of low initial cost per kilowatt by the following strategies:
     - No cylinder head modifications were required.
     - Stock diesel injector (with modifications) was used for pilot injection.
     - Continuous rating of 265 kW was achieved.

2. The operation of the CAT 3406 on one percent MicroPilot® was evaluated. Physical limitations were encountered in modifying the stock diesel injectors for one percent MicroPilot® operation.

   - Adequate spray patterns for 1% MicroPilot® could not be achieved with modified stock diesel injectors.
   - Operation of the 3406 genset on 1.2% lube oil pilot has been demonstrated.
   - The 3406 1.2% Lube Oil MicroPilot® genset did not meet the project goal of 1.5g/hp-hr NOx at 38% or greater thermal efficiency.
   - The 1% MicroPilot® system using the modified standard Caterpillar diesel injectors is not adequate for dual fuel pilot ignition.

3. The modification of the CAT 3412 diesel engine to MicroPilot® operation posed significant unanticipated challenges.

   - Physical layout of the V-12 engine and complexities with the intake manifold relative to the MicroPilot® installation on the CAT 3405 (6 cylinder) intake system.
   - Engine control unit output capacity limitations
   - The need for 2 gas valves per cylinder
   - Uneven firing order. It was determined that the 3412 engine is an uneven firing engine, whereas most 12-cylinder engines fire every 60°; the 3412 fires every 55° then 65°.
   - Natural gas injection system

- Fuel pump plate
- Electronic Pressure Regulator Block
- Air handling system
- After cooler system

4. Funding, market and time constraints resulted in the mutual agreement to terminate further development of the CAT 3412 MicroPilot® system.

- The diesel CAT 3412 genset was to be discontinued.
- The diesel fuel injectors for the CAT 3412, on which the CAT 3412 MicroPilot® is based, are being phased-out of production.
- The CAP electronic control unit does not have the capacity to support the 3412 MicroPilot® product. Using two of the current ECU's is difficult to implement and not a production viable solution. A new ECU development project is outside the scope of this project and would significantly lengthen the products time to market.

7.2. Benefits to California

- Additional options for low-cost environmentally preferred electric generation.
- Improved service through increased system reliability with the application of distributed power technologies.

7.3. Recommendations

1. Application of the CAT 3406 MicroPilot® genset for field service would require additional development.

- Additional software upgrades are required before the MicroPilot® system can be placed in service for additional testing and durability. These upgrades include:
  - Automatic starting and stopping routines.
  - Complete integration of ECU with generator control panel.
  - Speed governor upgrades are needed to accept sudden load changes on lube oil.
- Initial lube oil injection tests have shown that a smaller fuel pump driven with an electric motor is able to supply the same amount of rail pressure and fuel quantity for operation. This configuration should be investigated further due to the benefits of better starting, easier installation and lower cost.
- Design an optimized one percent MicroPilot® injector and retest lube oil and diesel NOx/thermal efficiency tradeoff.
- MicroPilot® operation with lube oil (in place of diesel fuel) would require additional development and systems.
  - Use of ashless lube oil is needed to be compatible with the MicroPilot® system. Ashless oil is not currently certified by the engine manufactures for engine durability. Therefore, to use lube oil as the MicroPilot® fuel, we need to certify (and possibly re-formulate) ashless lube oil for engine crankcase use.
  - Development of a lube oil pre-heat system for MicroPilot® injection during engine start. The lube oil needs to be heated to attain the proper spray characteristics for

cold engine start. Once the engine is at operating temperature, the lube oil temperature is adequate to maintain the proper spray characteristics.

2. Discontinue development of the CAT 3412 MicroPilot® system because of funding, market and time constraints.
    - Further develop and durability test the CAT 3406 MicroPilot® system for commercial introduction
    - Initial product introduction would be with the 2% MicroPilot® using diesel fuel injection.
    - Additional development is needed before lube oil MicroPilot® is commercially viable.
    - Exhaust after treatment systems need to be developed and tested to reduce the exhaust emission to lower levels.
3. Identify additional appropriate diesel engine gensets for future application of the MicroPilot® system.

8.0 Glossary/List of Acronyms

ACT	Air Charge Temperature
BMEP	Brake Mean Effective Pressure
BSCO	Brake Specific Carbon Monoxide
BSEC	Brake Specific Energy Consumption
BSHC	Brake Specific Hydrocarbons
BSNOx	Brake Specific Nitrogen Oxides
BTDC	Before Top Dead Center
CA	Crank Angle
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CPU	Central Processing Unit
ECT	Engine Coolant Temperature
ECU	Engine Control Unit
EGT	Exhaust Gas Temperature.
EOI	End of Injection

EPR	Electronic Pressure Regulator
EPROM	Electronically Programmable Read-Only Memory
GRI	Gas Research Institute
GTI	Gas Technology Institute
HC	Hydrocarbons
IMEP	Indicated Mean Effective Pressure
MAP	Manifold Absolute Pressure
NG	Natural Gas
NOx	Nitrogen Oxides
PC	Personal Computer
QCOM	Commanded quantity of fuel
RAM	Random Access Memory
SOI	Start of Injection
TAB	Turbo Air Bypass

Appendix I
Results of Endurance Test

I-1: Results of 60 Percent Load Test, 80 Hours

I-2: Results of 100 Percent Load Test, 20 Hours

Appendix II
Genset Control Logic Flowchart

Appendix III
Results of Lube Oil and Diesel Testing

III-1: Lube Oil Test Results From Cylinder Pressure Data

III-2: Diesel Test Results From Cylinder Pressure Data